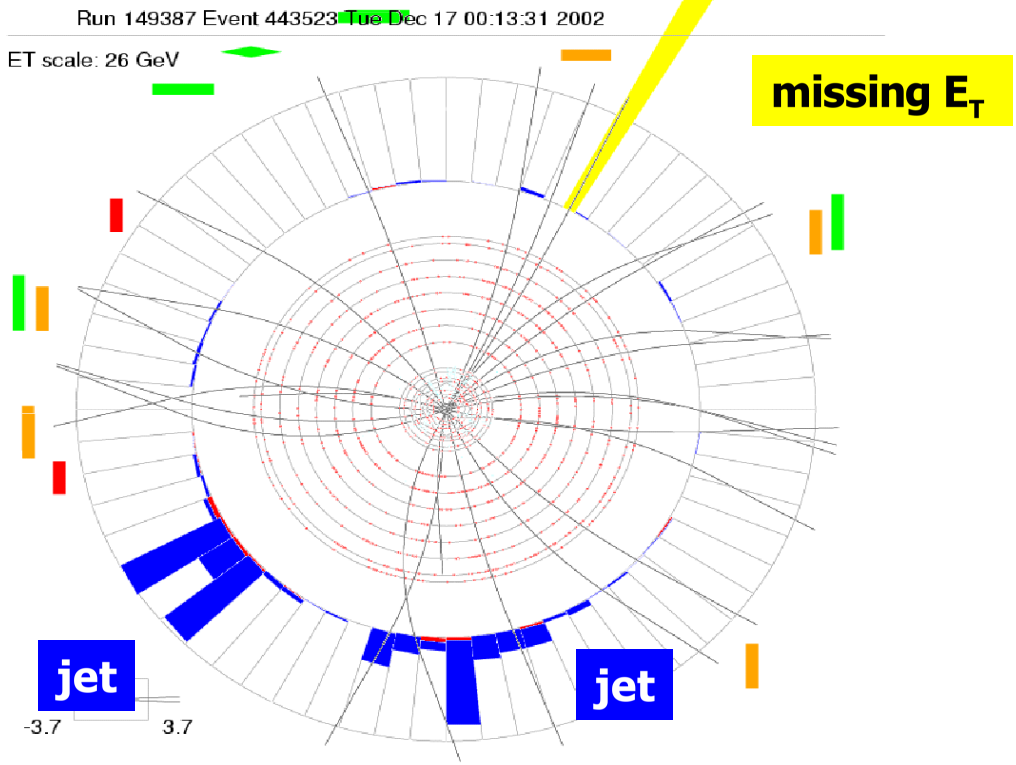
Discovery of Lightest Supersymmetric Particle at DØ



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MSU HEP Seminar, April 1 2004

Search for Single Top Quark Production

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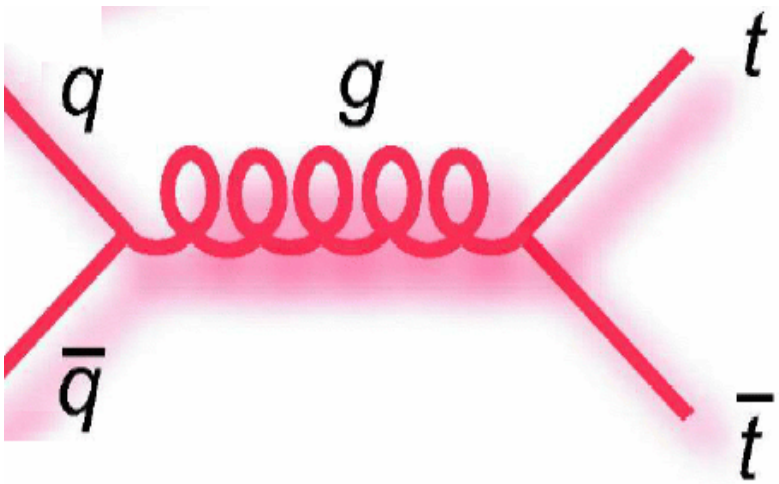
Outline

- Introduction
  - Single Top Quark Production
- Experimental Setup
  - DØ Detector
  - Trigger
- Search for Single Top Analysis
  - Preselection
  - Event Yield Estimates
- Results
- Conclusions
- Outlook

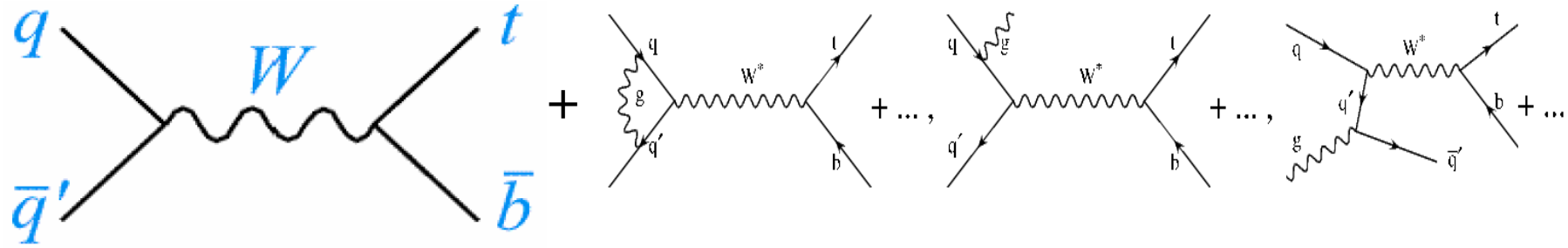
Introduction

- Tevatron is the highest-energy accelerator in the world
  - Test predictions of the Standard Model in detail
  - Search for new interactions not predicted by the Standard Model
- Only place in the world producing Top Quarks
- Top Quark
  - couples strongest to Higgs boson of all Fermions
    - predict Standard Model Higgs mass
  - use as probe for new interactions
    - study properties in detail
  - production mode: top pair production
    - study strong interaction in production
    - measure top quark mass, helicity

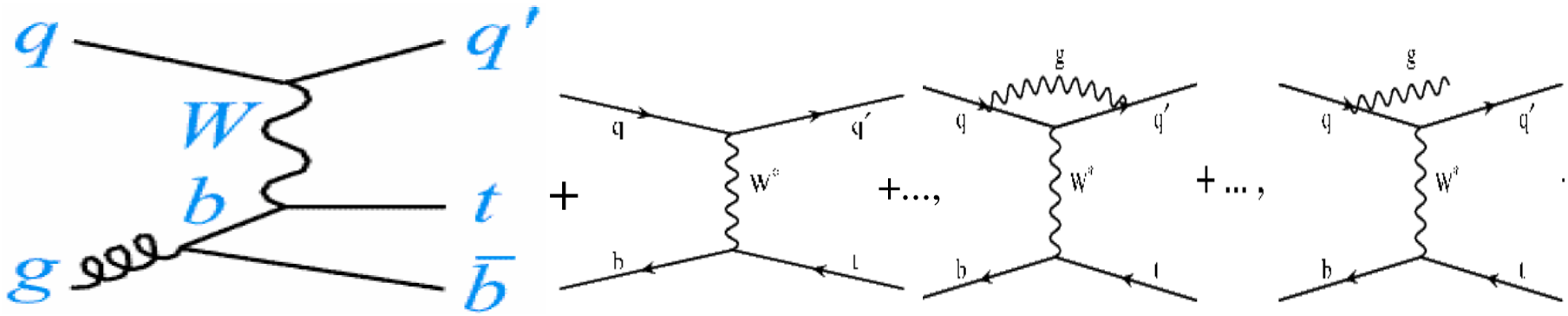


Single Top Quark Production

s-channel

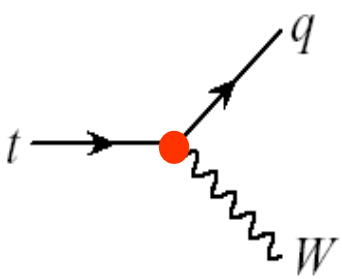


t-channel



- Electroweak production of top
  - Together with a b quark rather than a second top quark
- Single top quark production can be used to test predictions of the Standard Model
  - Measure CKM matrix element V_{tb} (test CKM unitarity)
  - Observe top polarization
    - Top Quark decays before it hadronizes

CKM Matrix and V_{tb}



$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Weak Interaction Eigenstates are not Mass Eigenstates
  - Mixing
  - Top quark must decay to a W plus d, s, or b quark

$$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} = 1$$

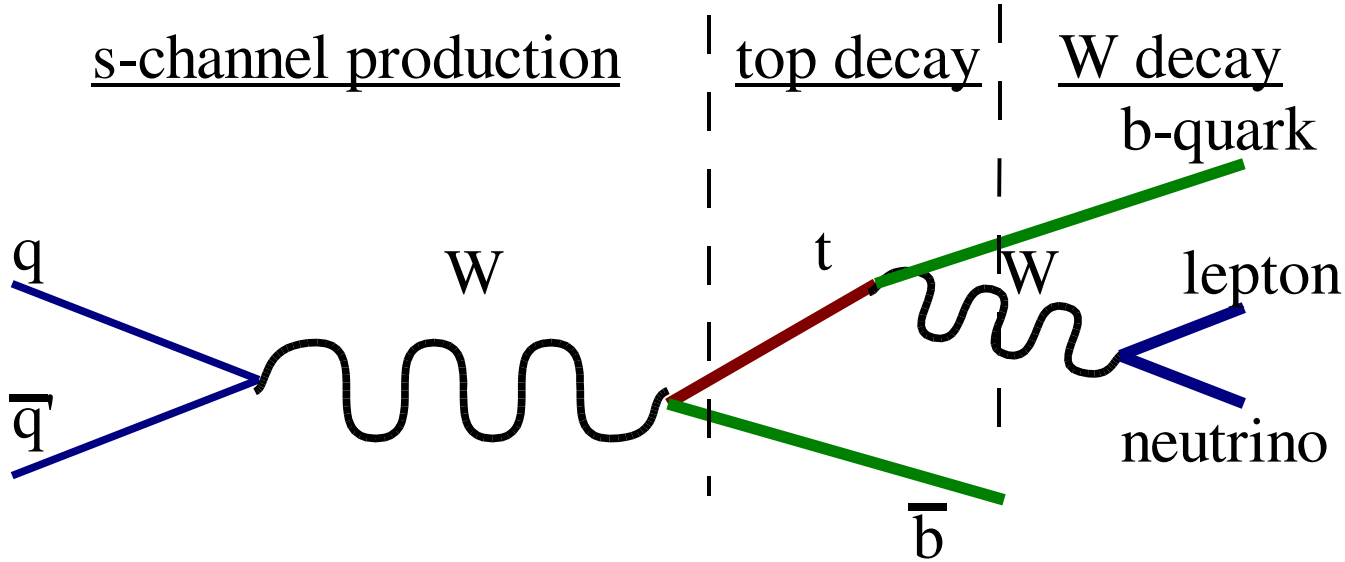
  - new Physics that couples to the top quark:

$$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} + V_{tx}^{\ 2} = 1$$

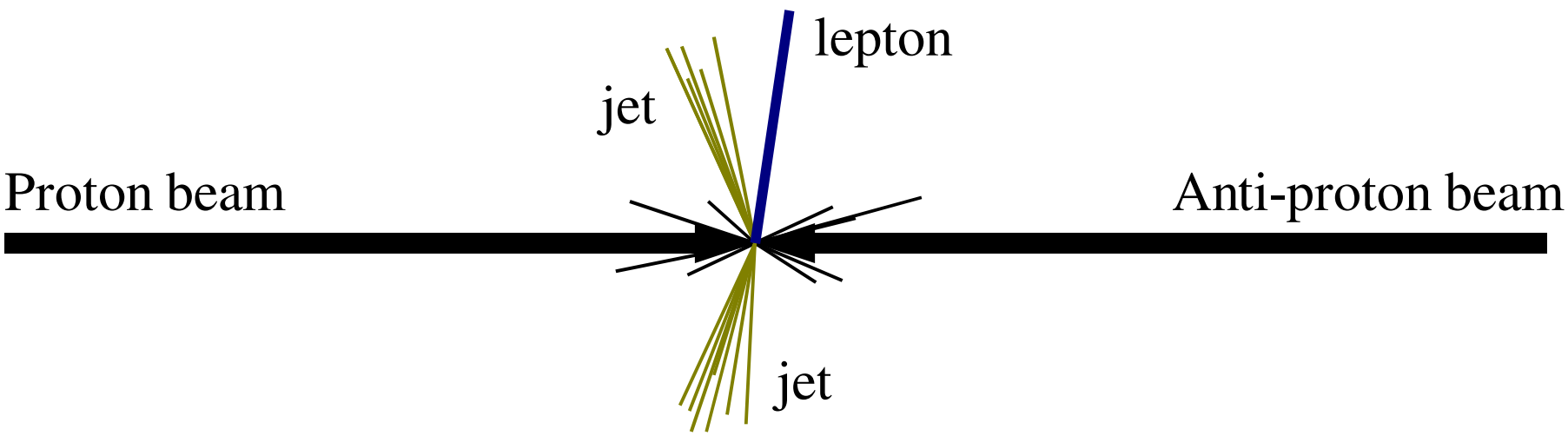
Single Top Search Status

- Single Top Production limits exist from Run I
  - based on ~100pb^{-1} of data
  - DØ: 95% CL: s-channel 17pb, t-channel 22pb
  - CDF: 95% CL: s-channel 18pb, t-channel 13pb
- We should be able to observe it in Run II
  - More data
  - Better b-quark tagging
  - Higher cross section (increased CM energy)
- NLO calculations now available
  - s-channel: σ = 0.88pb ± 16%
  - t-channel: σ = 1.98pb ± 15%
- Improved MC generators available

Single Top Event Signature

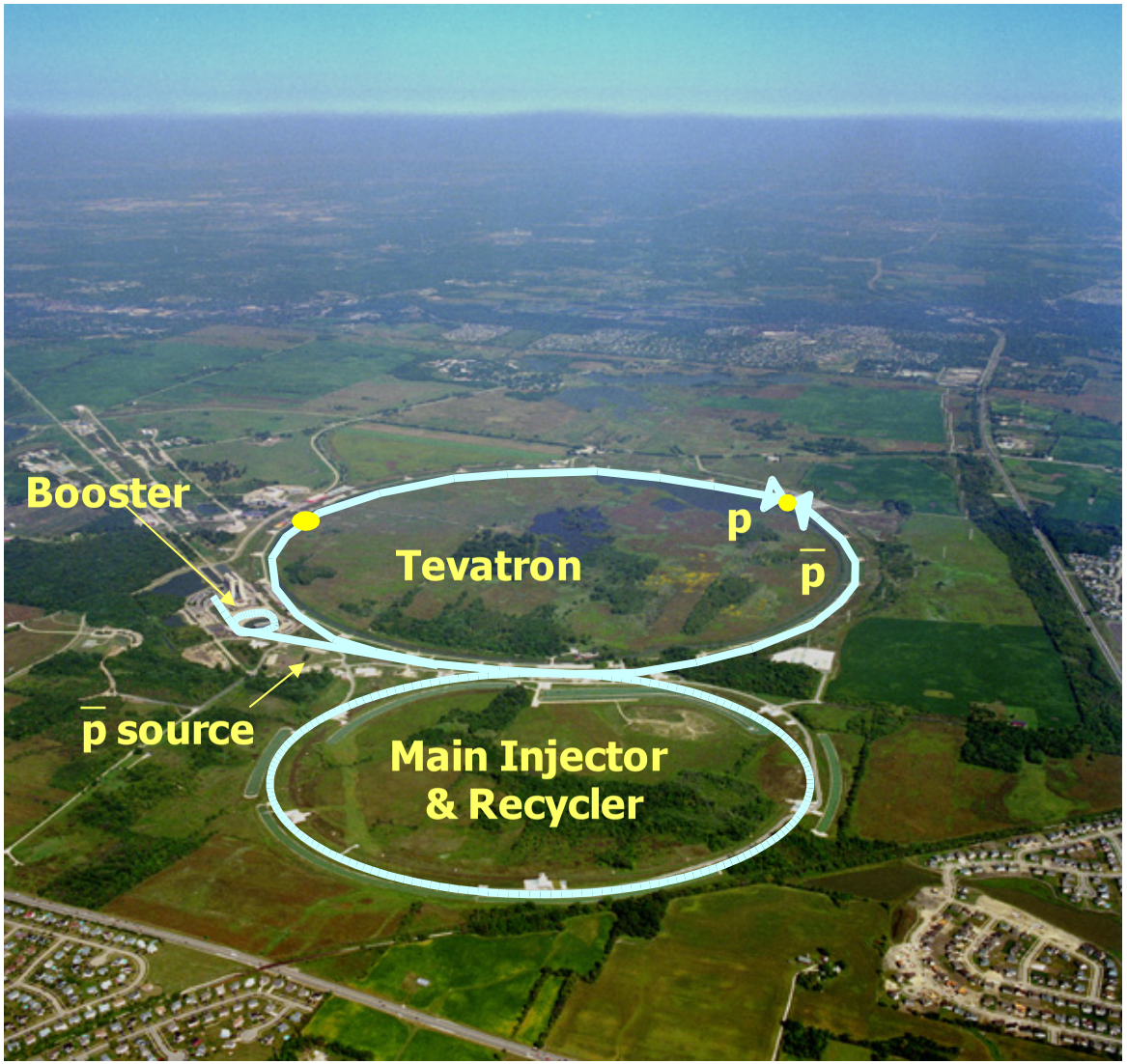


Final State Objects

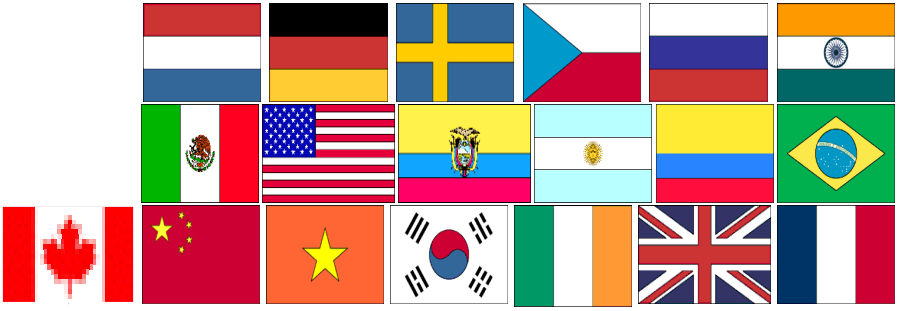


Experimental Setup

- Tevatron Run II started March 2001
  - proton-antiproton collider
  - E_{cm}=1.96 TeV
  - Peak L = 5 x 10^{32}
- Extensive Physics Program
  - Top Quark Studies
    - Precision Standard Model Measurements
  - W, Z
  - Higgs
  - New Phenomena
  - B-physics
  - QCD
- Preliminary DØ Single Top results in this talk
  - based on 160pb^{-1} of data



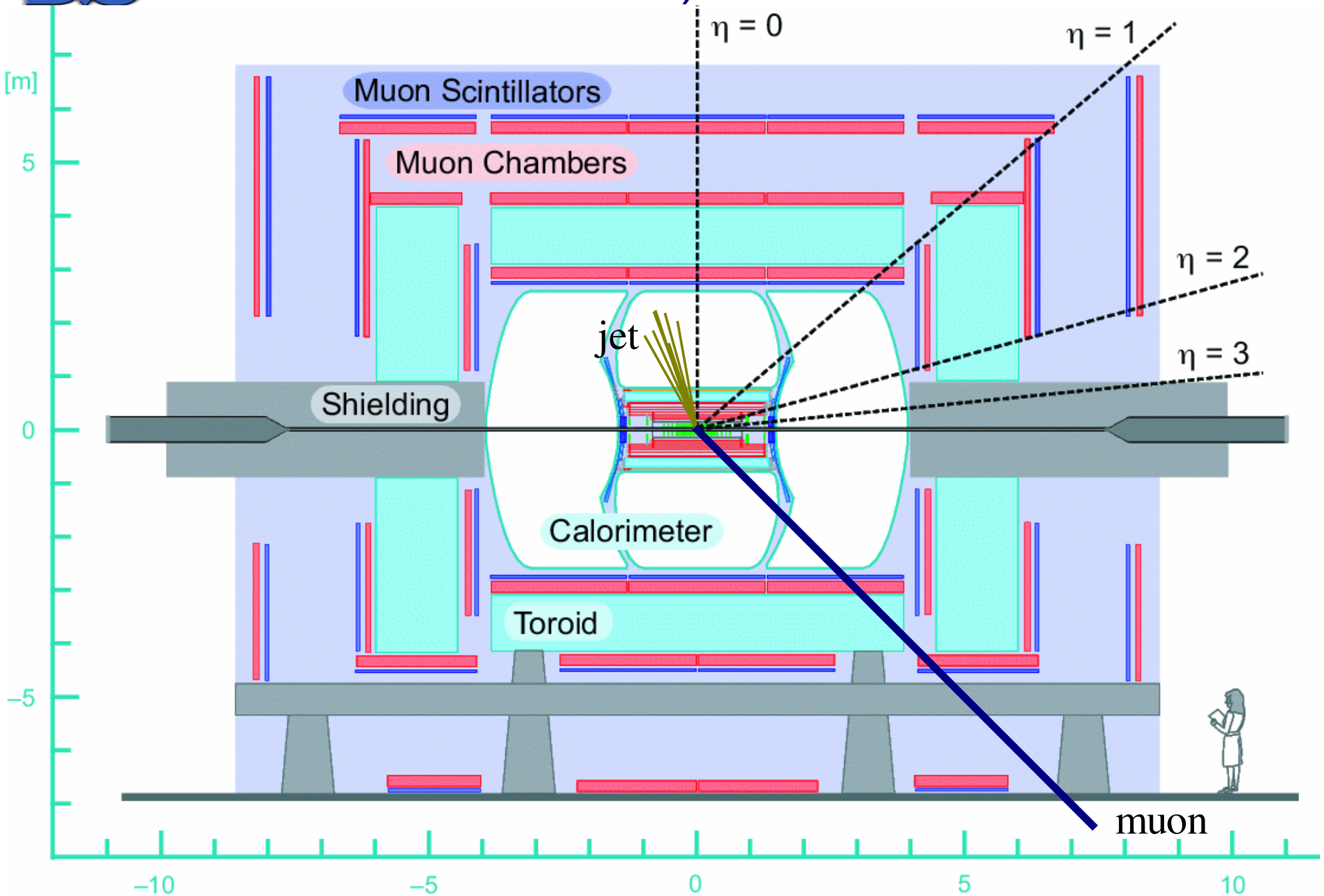
The DØ Collaboration



- 19 countries
- 80 institutions
- 670 physicists

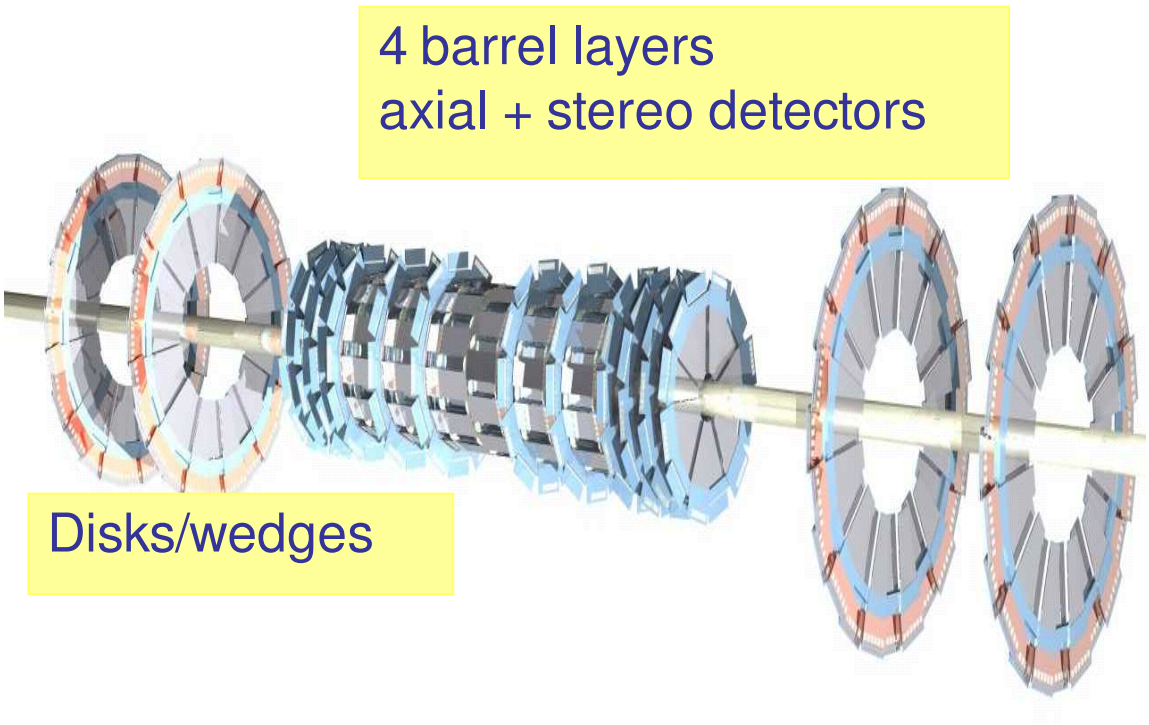
More than 50% non-US

Run II DØ Detector

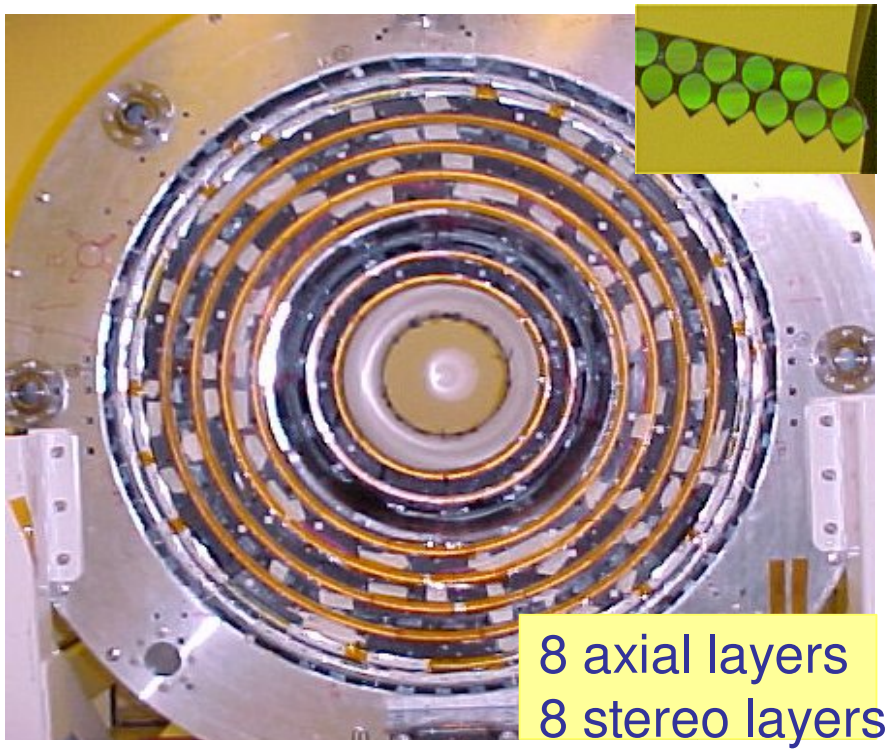


New for Run II DØ: Tracking Systems in 2T magnetic field

Silicon Vertex Detectors

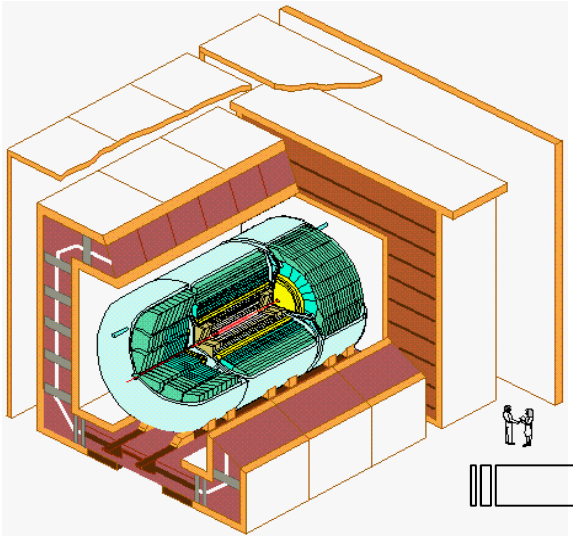


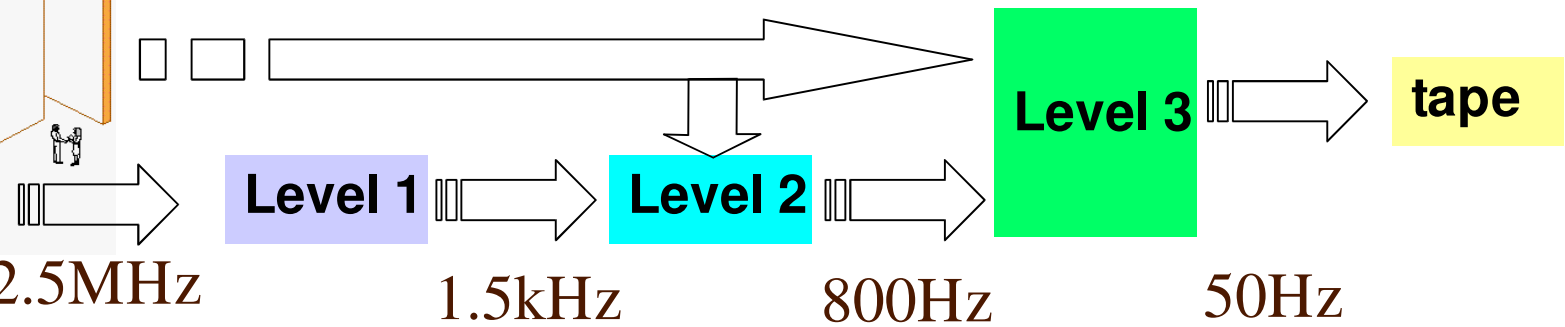
Central Fiber Tracker



- Improved momentum resolution for muons
- Track-based b-quark jet identification

Significantly Upgrade for Run II DØ: Triggering



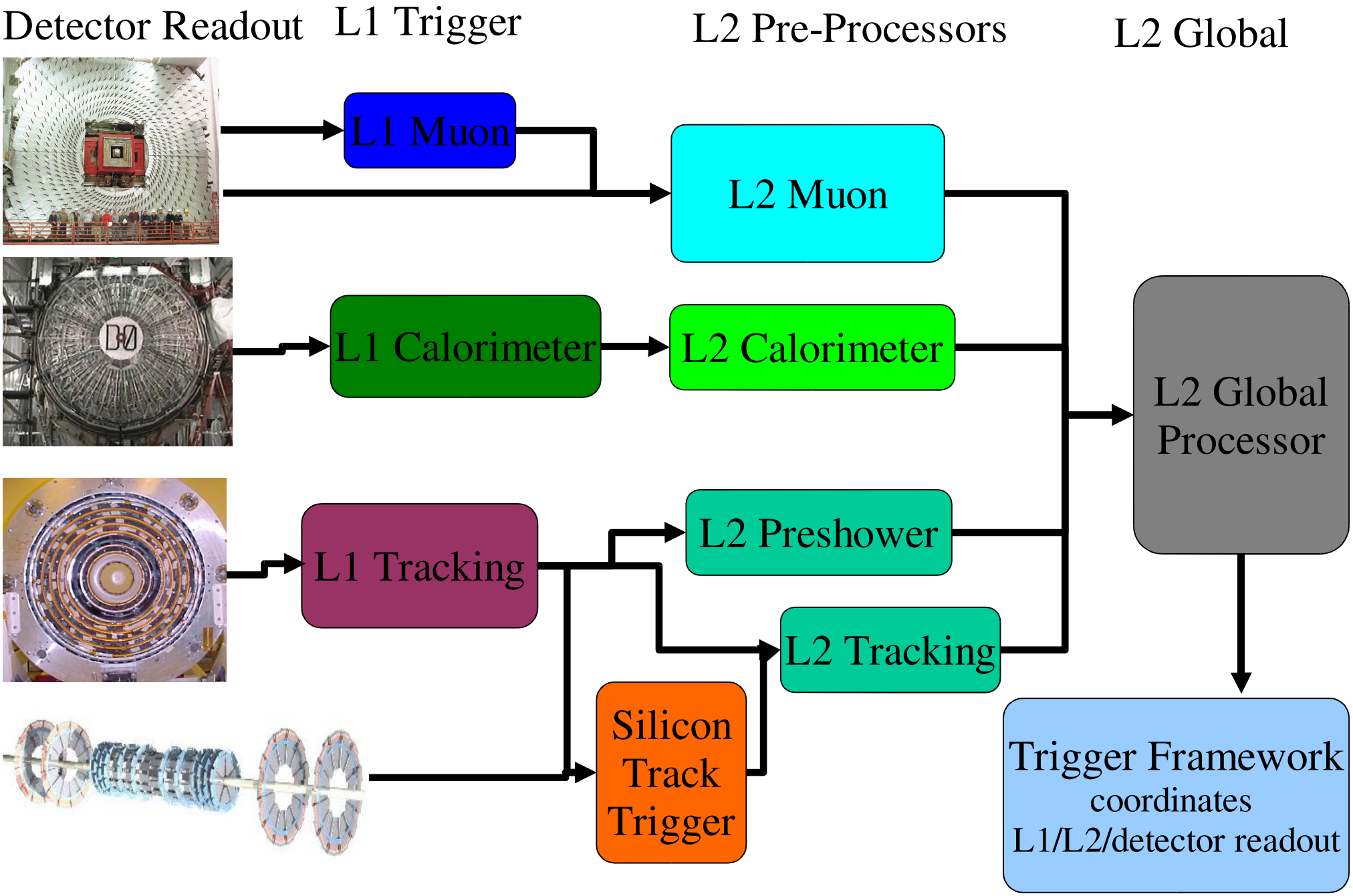


- Multi-level, pipelined, buffered Trigger Strategy
  - Level 1: one interaction every 396ns
    - fast trigger pick-offs from all detectors
    - custom hardware/firmware
      - one of Xilinx biggest customers
    - trigger on hit patters in individual detector elements
  - Level 2
  - Level 3
    - full detector readout
      - commodity based readout system (VME-based PCs and Ethernet switches)
    - processor farm to make trigger decision

Level 2 Trigger

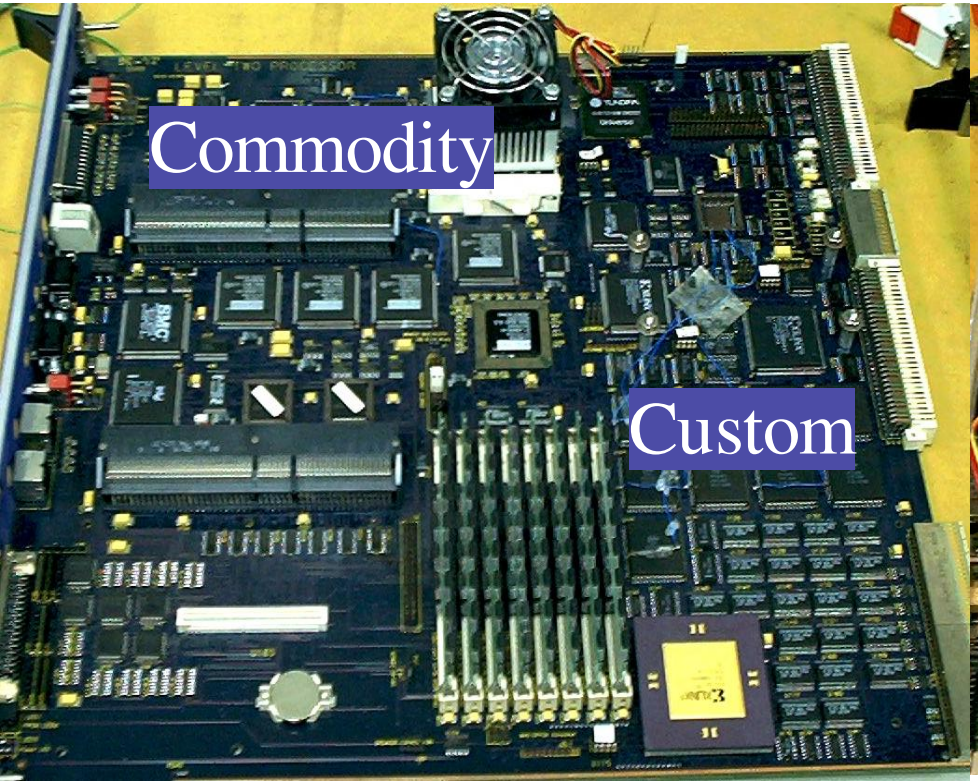
- Design: reduce 6kHz L1 accept rate to 1kHz
- Both custom hardware/firmware and commodity-based components
  - Dataflow from L1 and detector systems in custom systems
  - Algorithms in software running on commodity-based system
- Build Physics objects
  - Jets and EM objects are built from L1 calorimeter towers
  - Central tracks are built from L1 track trigger tracks
  - Muons are reconstructed from from raw muon detector hits
- Combine objects from different detector systems
  - Track matching to muons, electrons, or jets
- allow for 128 different combinations
  - 1-1 matching of bits L1/L2

Level 2 Dataflow



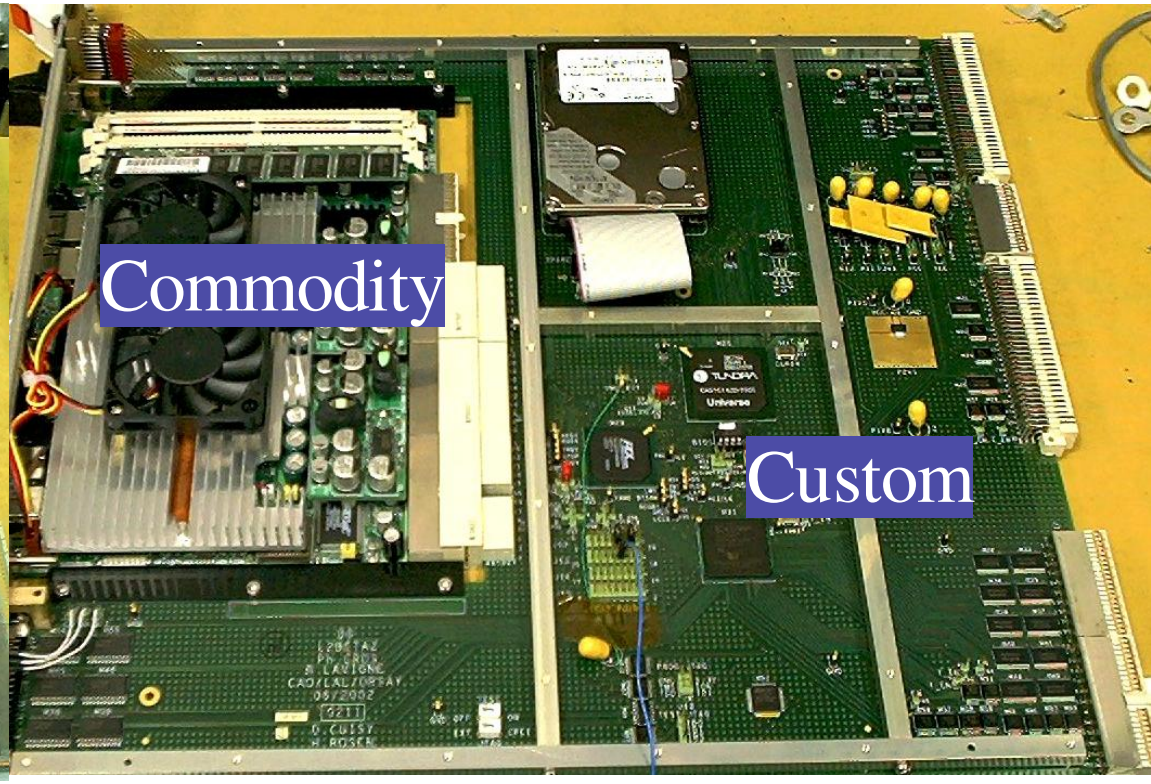
Custom Interfaces to Commodity Hardware

Alpha Processor



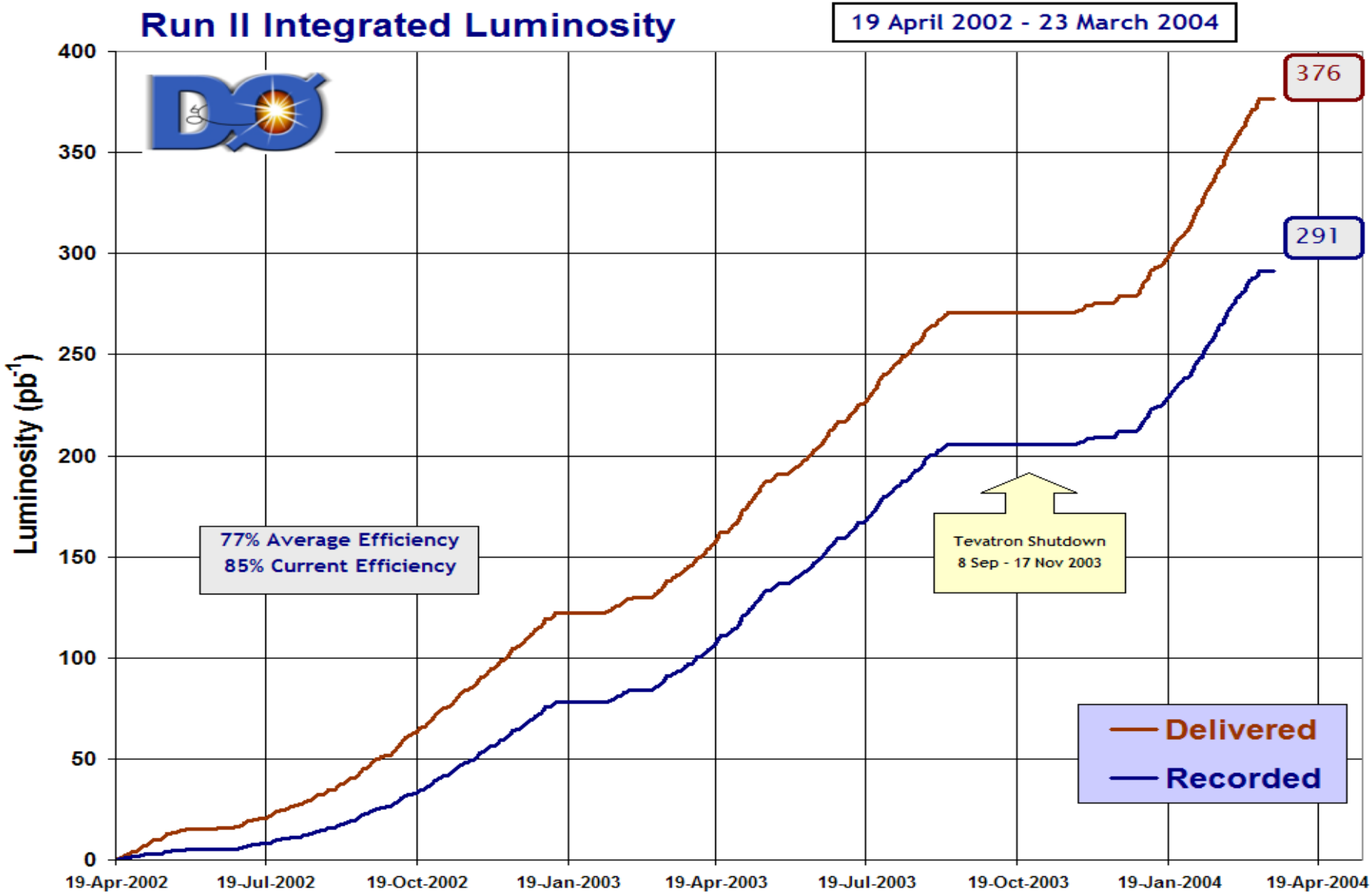
- 500MHz Alpha processor, memory, PCI bus on same board as custom dataflow interface

Beta Processor



- custom dataflow card
- 1GHz dual-Pentium processor on separate card
  - standard industrial card
- straightforward to upgrade

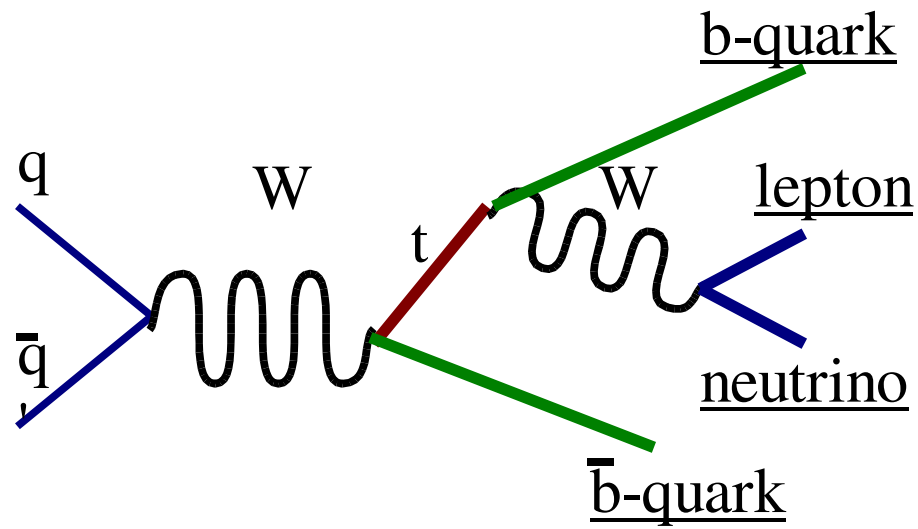
Accelerator/Detector Performance



- Recorded over 250pb^{-1} to date
- Hope to double by end of year, 4-6 fb^{-1} of data by 2009

Selecting Single Top Events

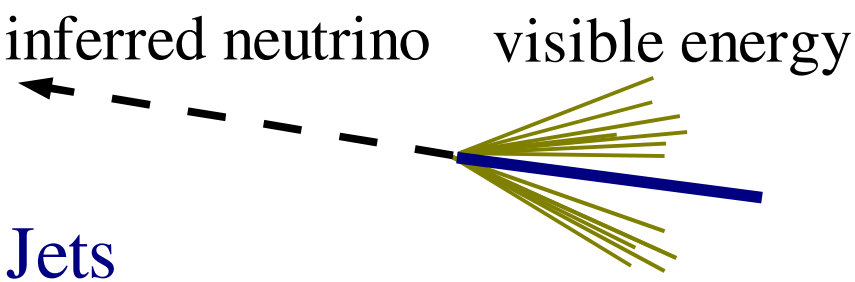
- Single Top Event Signature:
  - One high-pt lepton (electron, muon)
  - Transverse energy imbalance (neutrino)
  - One b-quark jet (from top decay)
  - More jets (light quark-jet, another b-jet)



- Backgrounds
  - Mis-reconstructed multi-jet events
  - W+jets production (Wjj, Wcc, Wbb, etc)
  - Top pair production
    - One W from top decays to a lepton
    - Both Ws from top decay to leptons (one lepton mis-identified)
  - Others (WZ, WW, $Z \rightarrow \mu\mu$+jets, cosmic rays)

Final State Reconstruction

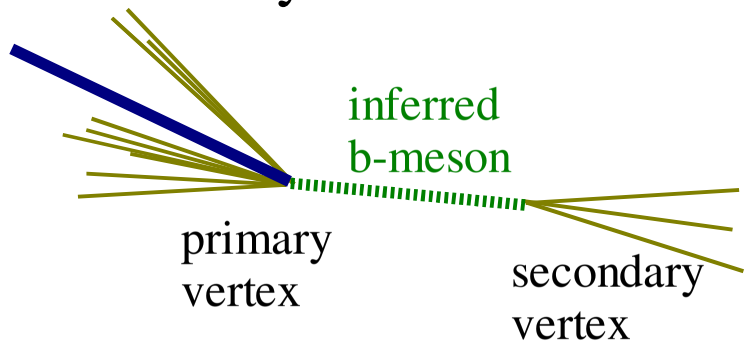
- Lepton
  - Electron: tracking, calorimeter
  - Muon: tracking in central tracker and muon system
- Neutrino
  - Indirectly through energy imbalance in transverse plane



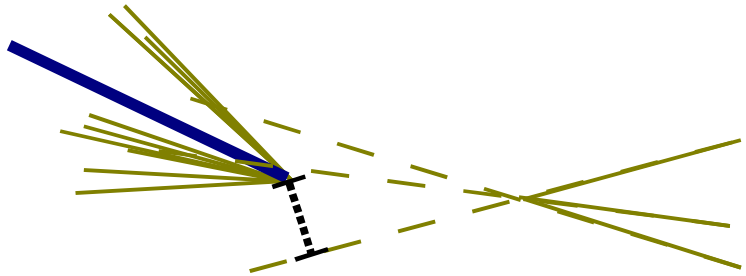
- Jets
  - clustering calorimeter energy
  - corrected to get particle pT

- b-quark identification
  - Muon from b-meson decay
  - Tracking-based lifetime tagging

Secondary Vertex Reconstruction



Impact Parameter Tag



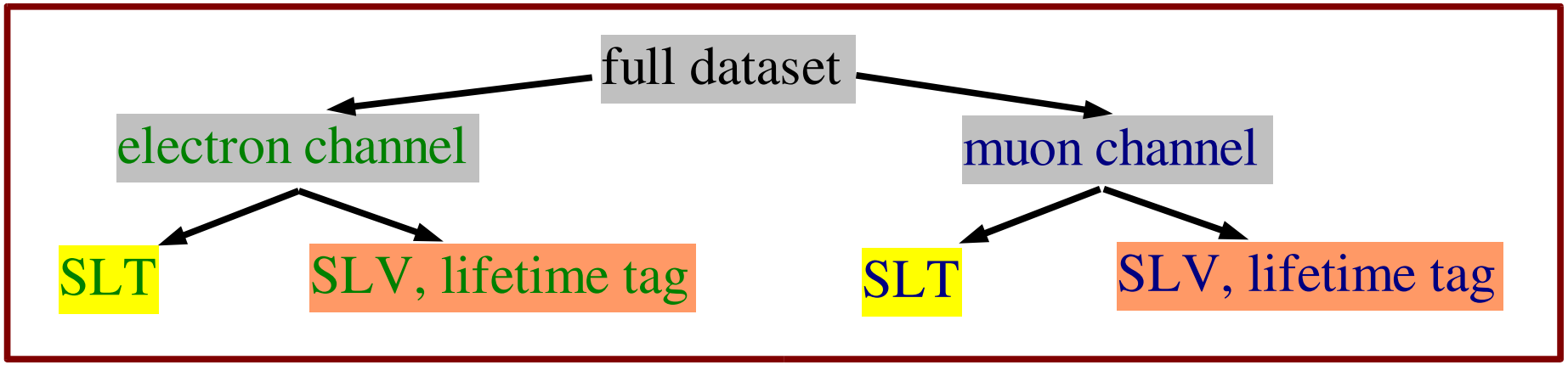
Probability for each track in the jet to originate from the primary vertex

2 Step Analysis

- Preselection based on Single Top Event Signature
  - Select events containing W and jets
    - Loose requirements to suppress huge QCD background
  - Require b-quark tag
    - Loose requirement to suppress large non-top quark background
  - Study background estimation in detail
    - Prove background model reproduces data
- Final Event Selection
  - Separate single top from top pair production
    - Number of jets, total energy in the event, etc.
  - Separate single top from W production
    - Total energy in the event, reconstructed top mass, etc.
  - Separate s-channel from t-channel

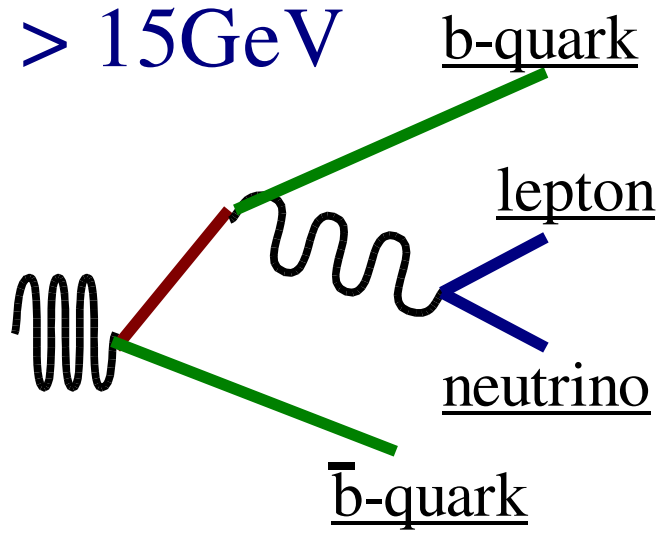
Analysis Channels

- Split data into orthogonal channels
  - electron channel ⇔ muon channel
    - Veto on events containing the other lepton
  - soft-muon-tagging (SLT) ⇔ lifetime tagging
    - Lifetime tagging analyses apply SLT Veto
    - Use several lifetime tagging methods for cross-check
      - Not orthogonal, cannot combine
- Derive single top limit in each channel
- Combine limits from orthogonal channels



Preselection Cuts

- Lepton: 1 electron or muon, pT > 15GeV
- Neutrino: missing transverse energy > 15GeV
- Jets:
  - pT > 15GeV
  - $2 \leq n \leq 4$
  - leading jet pT > 25GeV



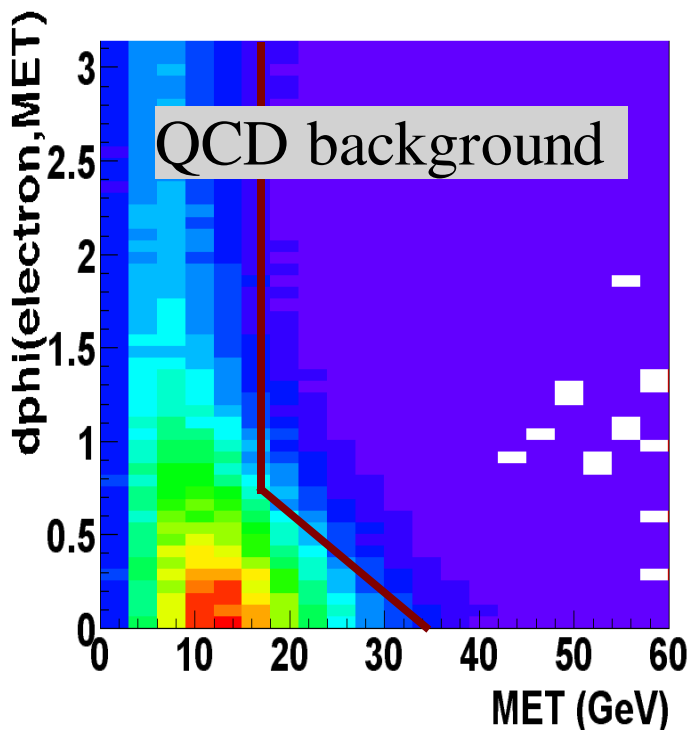
- Trigger:
  - L1: Lepton: ≥1 EM object, pT>10GeV or ≥1 muon hit Jets: ≥1 jet
  - L2: Lepton: ≥1 EM object, pT>12GeV or ≥1 muon Jets: ≥ 1 jet
  - L3: Lepton: ≥1 EM object, pT>15GeV Jets: ≥ 1 jet
  - efficiency: ~85% (electron channel), ~89% (muon channel)
- Reject mis-reconstructed events

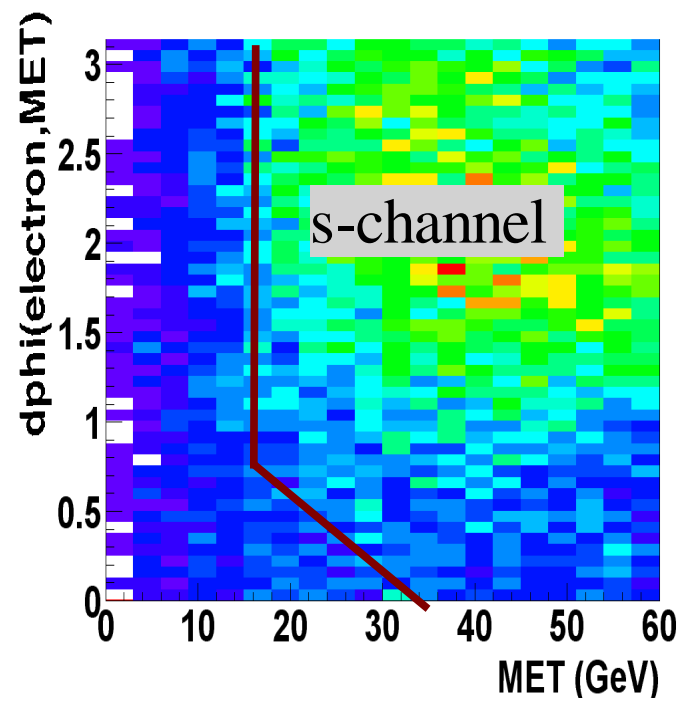
Mis-Reconstructed Events

- Cosmic rays (muons)
- Mis-reconstructed vertex
  - Affects missing transverse energy
- Mis-reconstructed jets
  - fake electron
  - fake isolated muon

➔ Primary vertex constraints
  - Primary vertex with ≥3 tracks
  - Lepton is required to come from primary vertex

➔ Triangle Cuts





Background Estimate: Preselected Sample

- Purpose:
  - Make sure background model is accurate
    - List of background sources is complete
    - Background estimation methods work
  - Check sensitivity of the analysis
- Preselected sample dominated by backgrounds
- Preselected sample is large
  - Check shapes of distributions, not only total count
  - Check relative contribution from different background sources
- Use data as much as possible
  - for background estimation
  - to determine efficiencies

Background Estimate: pre-tagging

- Preselected, Pretagged sample contains two components:
  - Events with *real* isolated lepton
  - Events with *fake* isolated lepton
    - Jet faking an electron
    - Muon in jet faking isolated muon
- Matrix Method to estimate relative contribution
  - Count events before/after a cut that separates the two (loose/tight)
    - Electron channel: electron likelihood cut (combination of cal/tracking)
      - Background efficiency e_{QCD} determined in multi-jet QCD sample (low MET)
      - Signal efficiency e_{sig} determined in Zee sample
    - Muon channel: muon isolation from jet
      - Background efficiency e_{QCD} determined in QCD sample (low MET)
      - Signal efficiency e_{sig} determined in Zmm sample

Pre-tagged Background Yield

$$N_L = \tilde{N}_{sig} + \tilde{N}_{QCD}$$

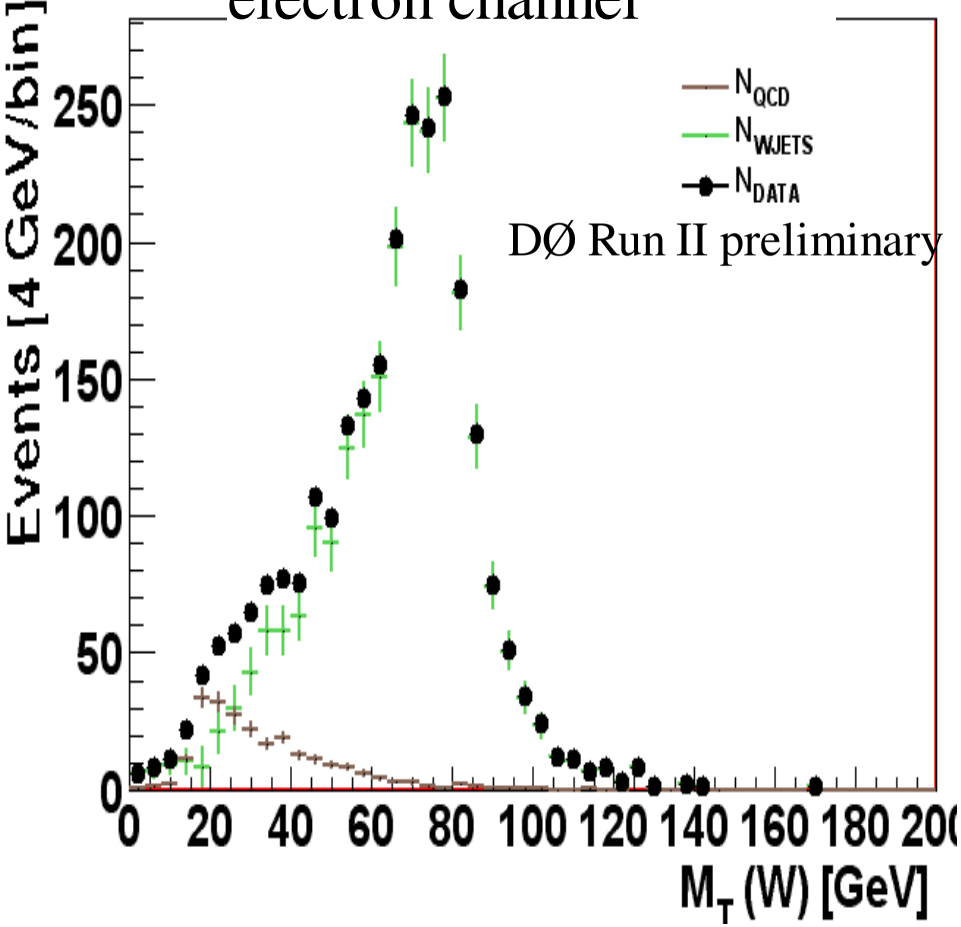
$$N_T = \varepsilon_{sig}\tilde{N}_{sig} + \varepsilon_{QCD}\tilde{N}_{QCD}$$

$$\Rightarrow$$

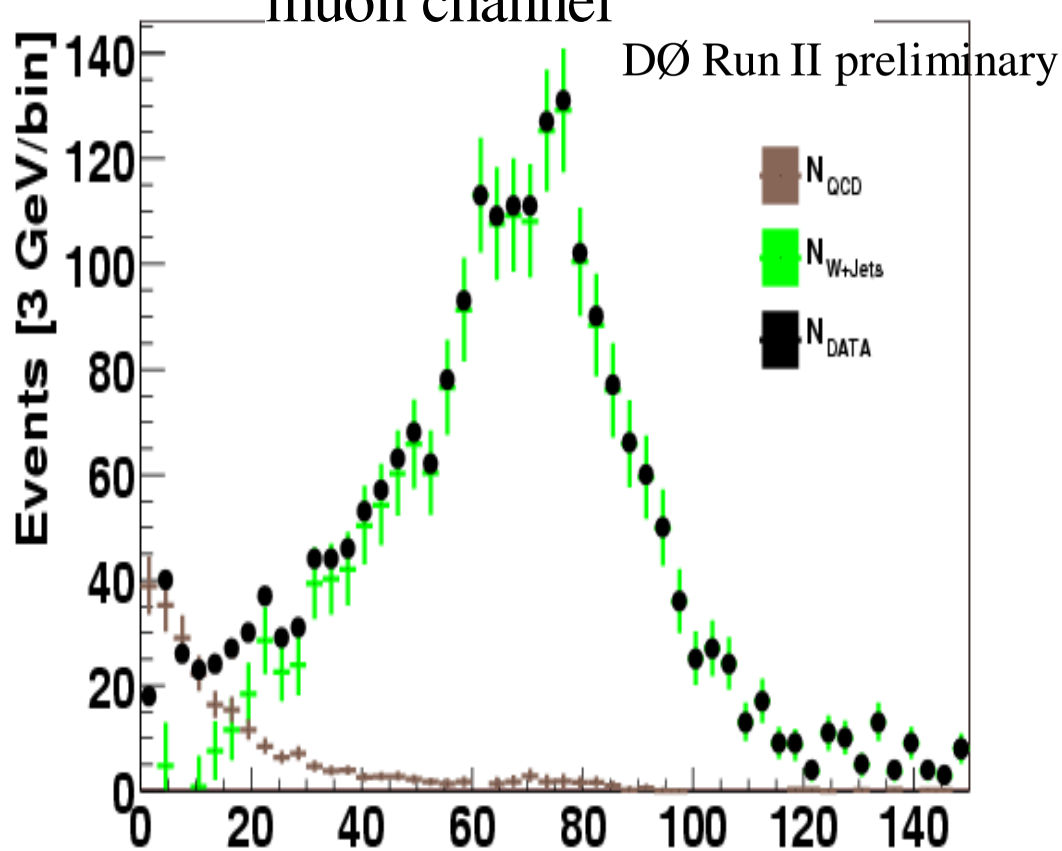
$$\tilde{N}_{sig} = \frac{N_T - \varepsilon_{QCD} N_L}{\varepsilon_{sig} - \varepsilon_{QCD}}$$

$$\tilde{N}_{QCD} = \frac{\varepsilon_{sig} N_L - N_T}{\varepsilon_{sig} - \varepsilon_{QCD}}$$

electron channel



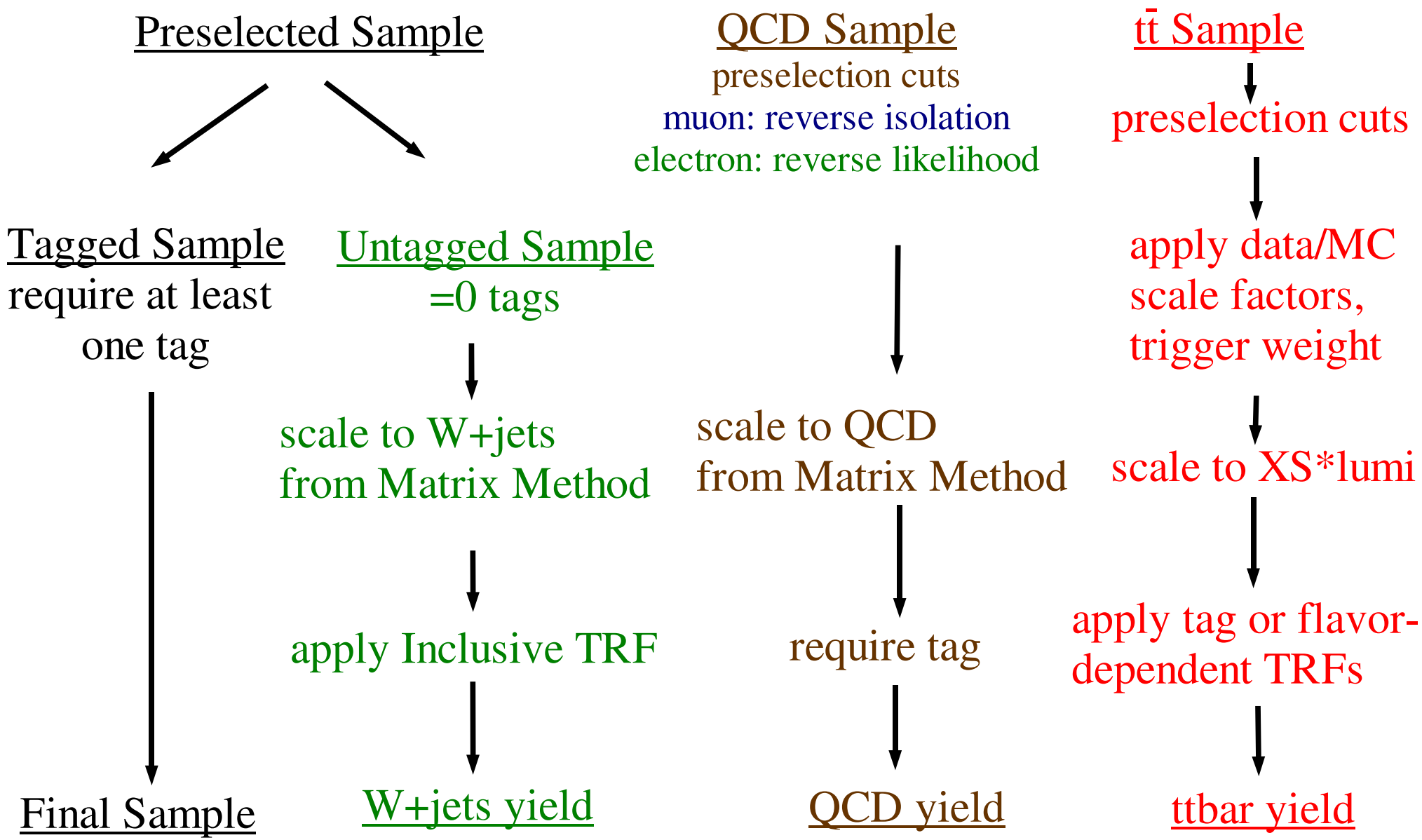
muon channel



Background Estimate: tagged

- Data backgrounds: divide preselected sample into orthogonal sets
  - Tagged signal data
    - Require at least one jet to be tagged
  - Un-tagged sample for W+jets background
    - Require that none of the jets be tagged
  - Multi-jet sample with fake isolated leptons for QCD
    - Lepton fails tight cut
- MC for signal and top pair production background
- Check prediction in W, QCD-dominated sample
  - Suppress ttbar, single top:
    - $n_{jets}=2$
    - total energy in the event HT<200GeV

Tagged Background Estimation

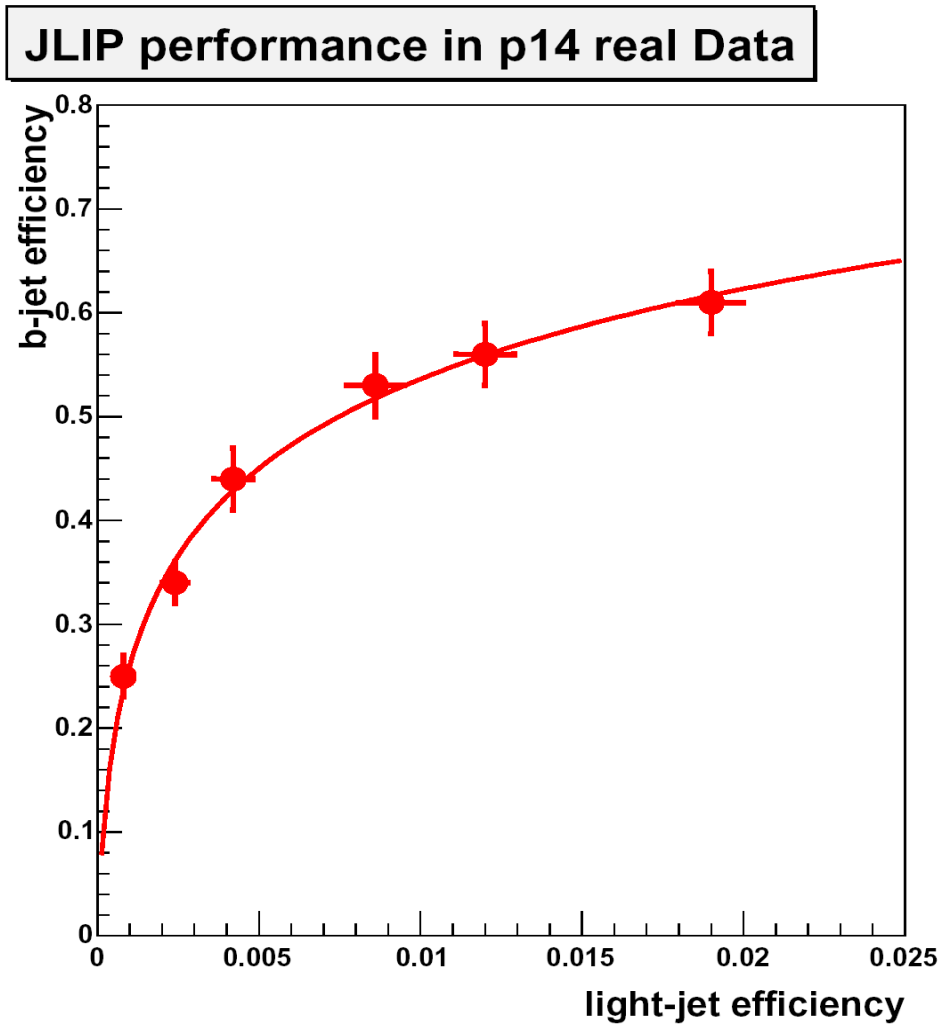


Background Sample Normalization

- QCD
  - Normalize orthogonal, QCD-like sample to QCD estimate from pre-tagged sample
    - electron: fail likelihood cut, muon: fail tight isolation cut
  - Apply tagging directly to this sample
- W+jets
  - Normalize un-tagged sample to W+jets from pre-tagged sample
  - Assign weight based on probability to find tagged jet
    - derived on a QCD multi-jet sample
    - assumes same (within uncertainty) jet flavor composition as W+jets
- MC (top pair, single top signal)
  - Normalize to cross section times luminosity
  - Assign weight based on probability to tag jet of given flavor

Simulation of b-quark tagging: Tag-Rate-Functions

- b-quark tagging efficiency is over-estimated in the Monte Carlo for lifetime taggers
  → cannot require tag in MC
- measure tagging efficiency in data
  - flavor-dependent: separate efficiencies for b, c, light quark jets
  - then apply as weight to each MC jet



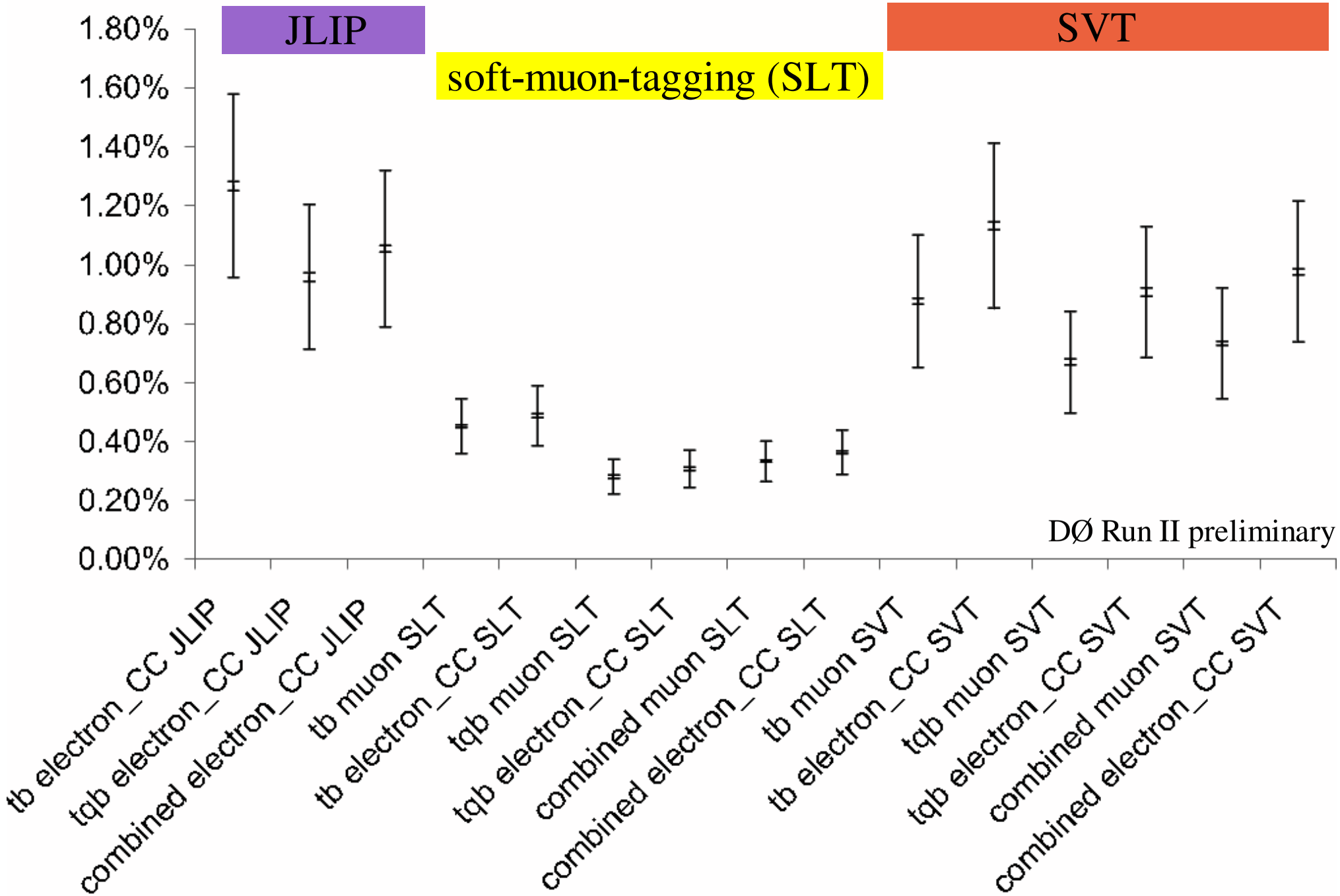
Flavor-Inclusive TRF

- W+jets background estimate from data:
  - Average probability to tag a jet in an inclusive W+jets sample
  - ➔ Approximately same as in multi-jet sample
    - Flavor-inclusive tag-rate function (TRF)
  - Determine per-jet probability in multi-jet sample (1-3%)
    - Then apply as weight to each jet in untagged W+jets sample
- Test flavor-composition assumption
  - In Z+^{3}2 jets sample
    - Limited statistics
  - In W+jets cross-check sample (n_{jets}=2, HT<200GeV)
  - Find good agreement in all samples

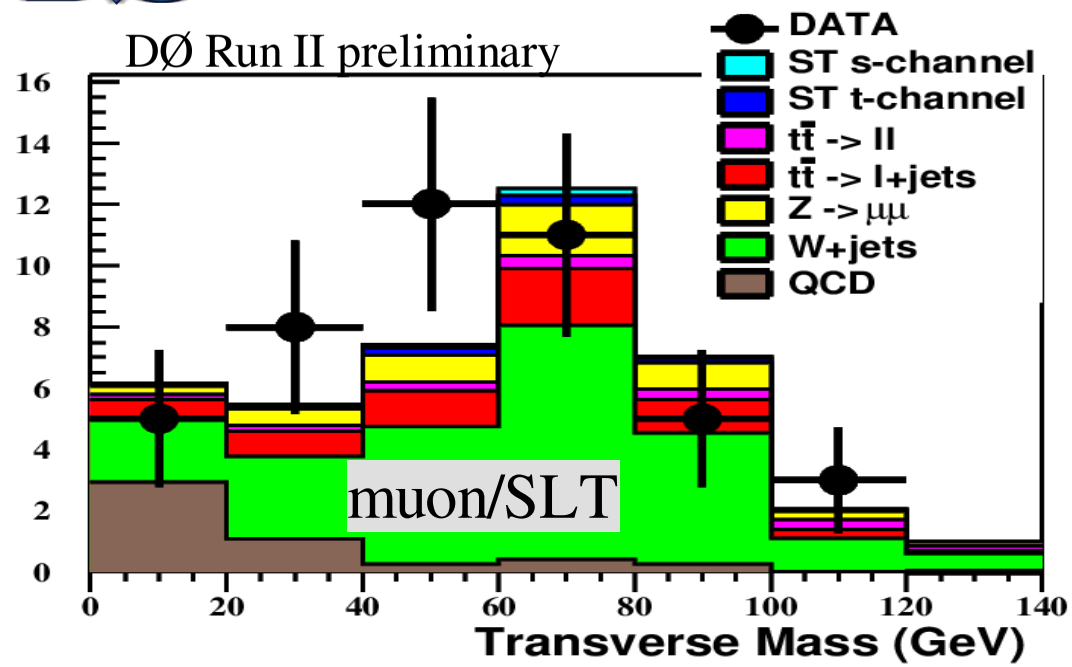
Systematic Uncertainties

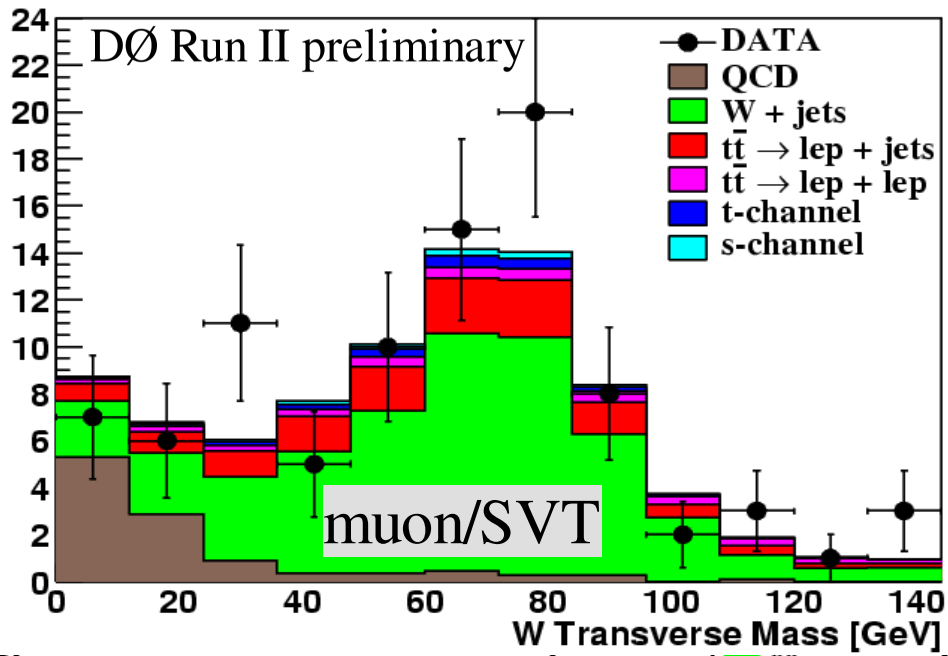
- MC (acceptance and ttbar bkgd):
  - luminosity: 6.5%
  - branching fraction: 2%
  - electron ID: 2.4%
  - muon ID: 6.3%
  - SLT:
    - tagging muon modeling: 2.6%
    - tagging muon ID: 2.1%
  - SVT, JLIP:
    - tagging muon veto: 3.3%
  - primary vertex: 0.6%
  - trigger parameterization: ~10%
  - L1 trigger eta change: 4%
  - jet fragmentation: 5%
  - Jet Energy Resolution: 0.5%
  - Jet Energy Scale: ~3%
  - flavor-dependent TRF: ~12%
- Data (QCD and W+jets):
  - QCD scale factor: ~13%
  - W+jets scale factor: ~3%
  - inclusive TRF: 20%

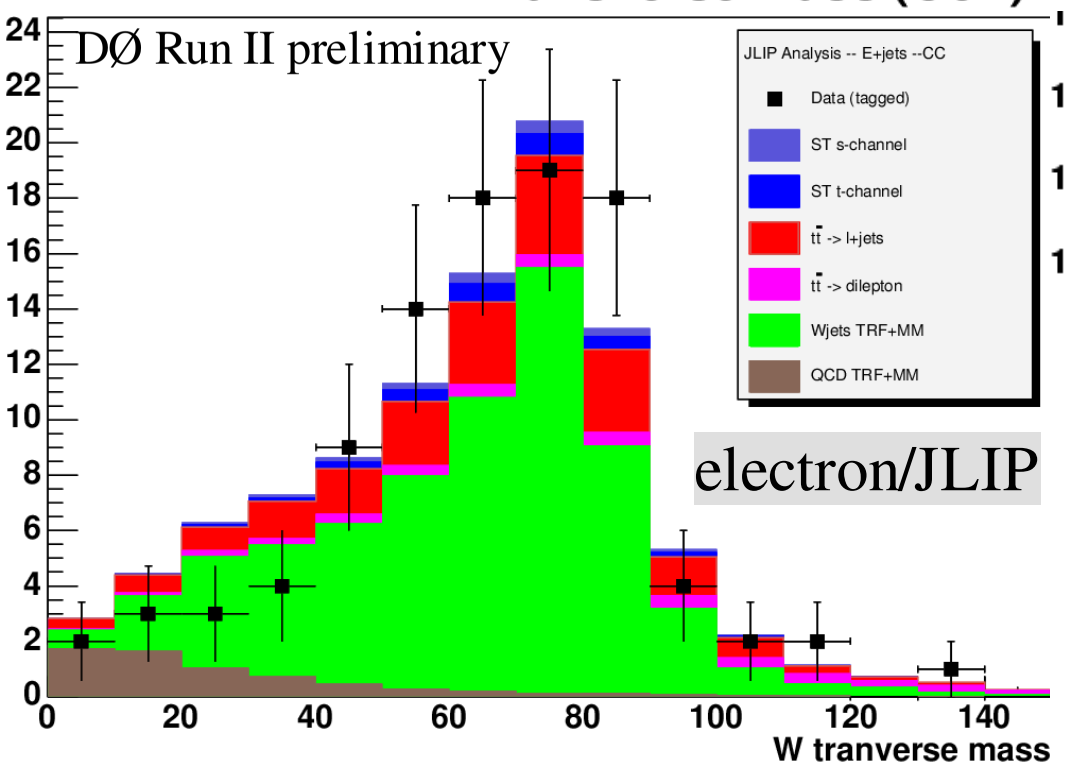
Signal Acceptance

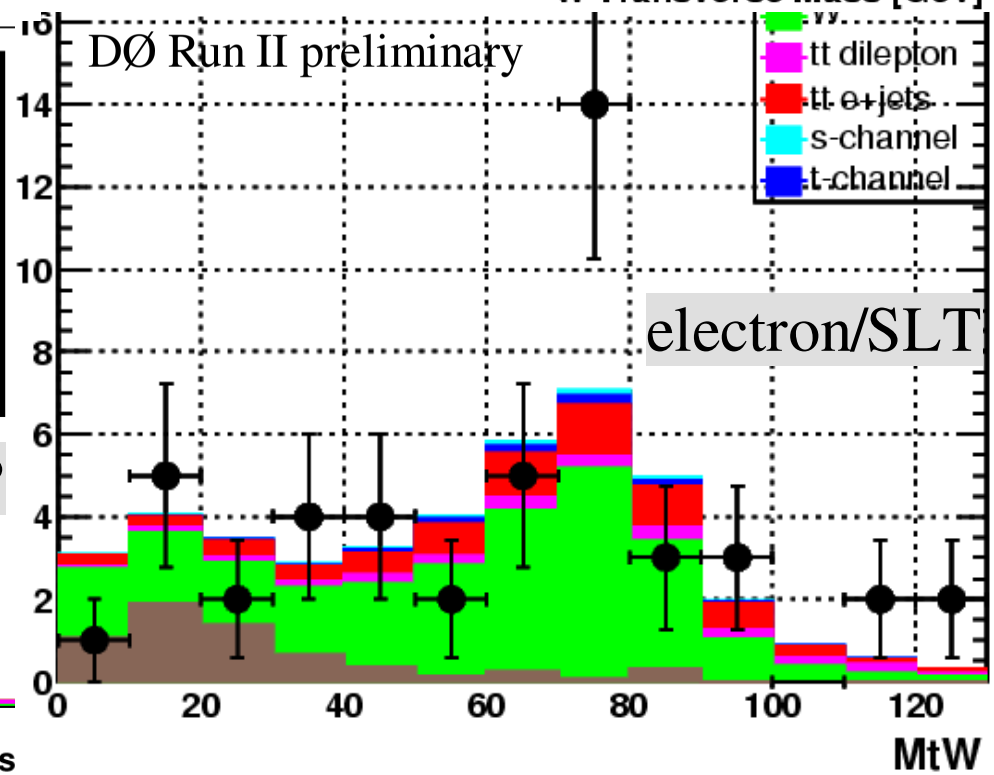


Event Yields: W Transverse Mass

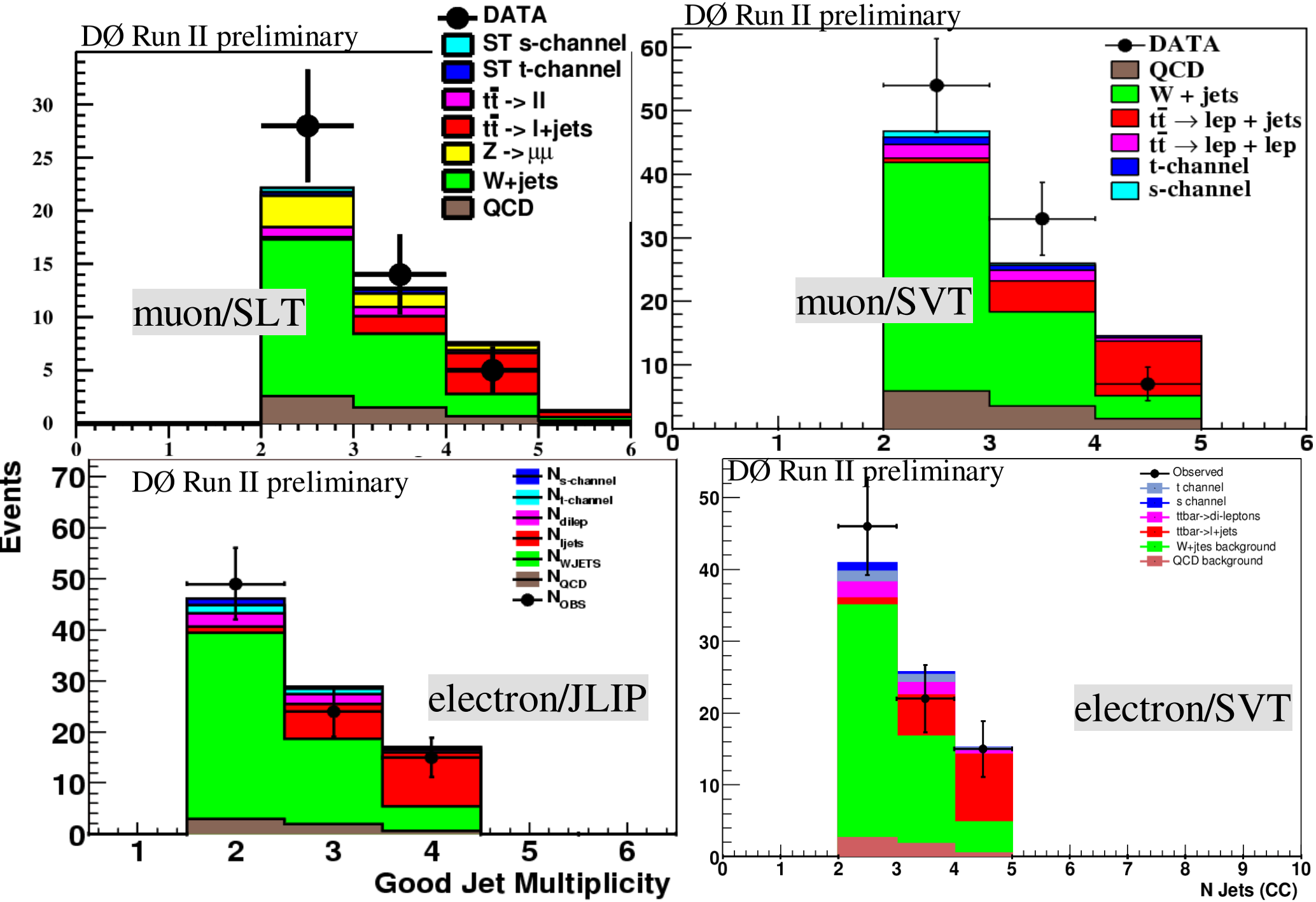




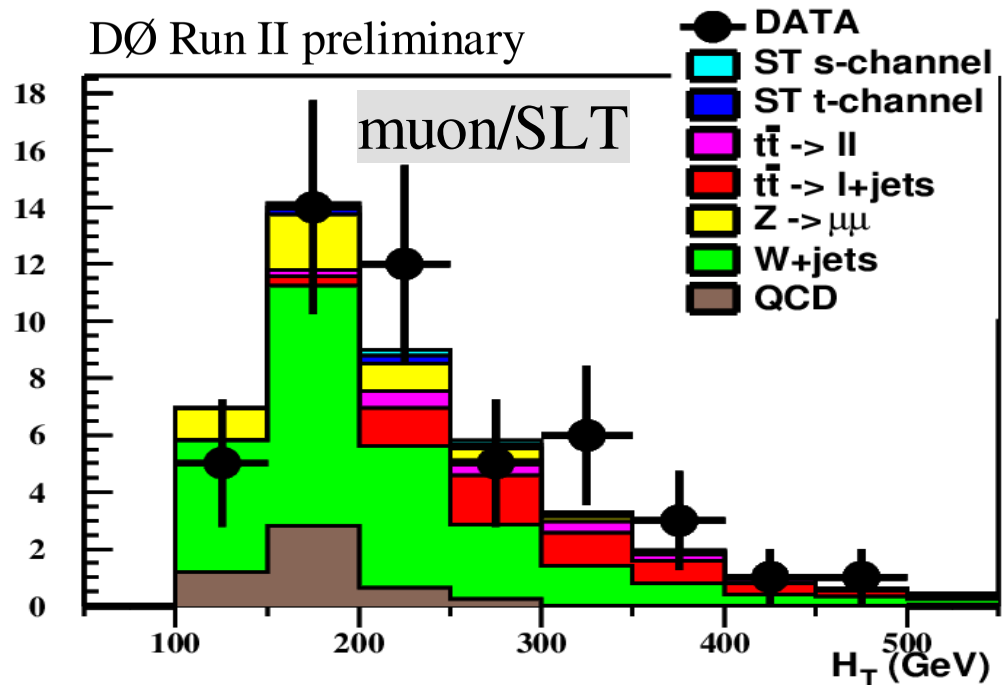


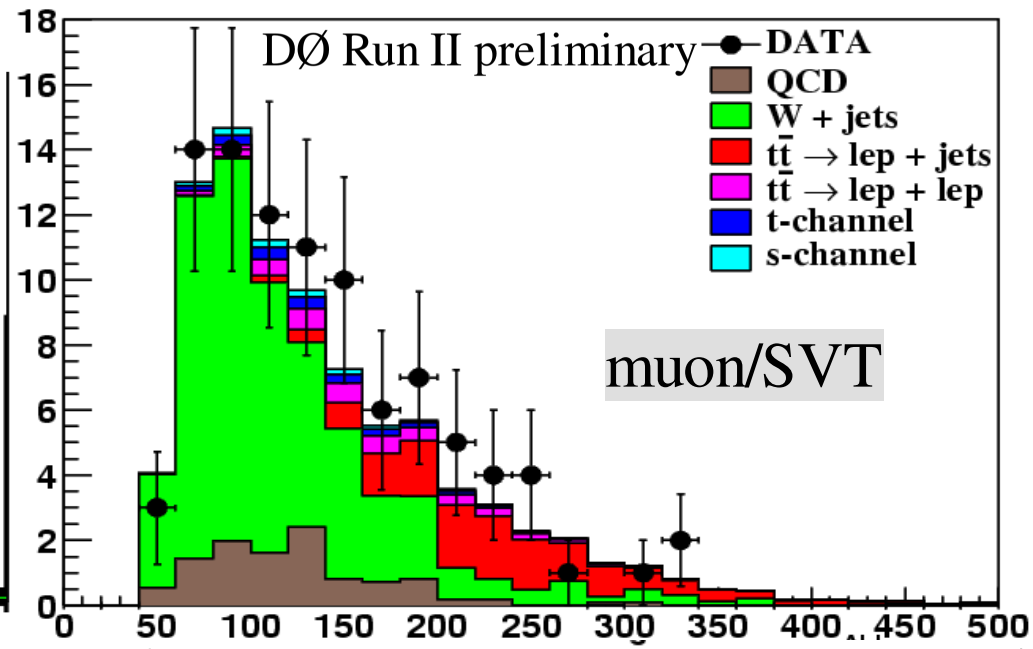


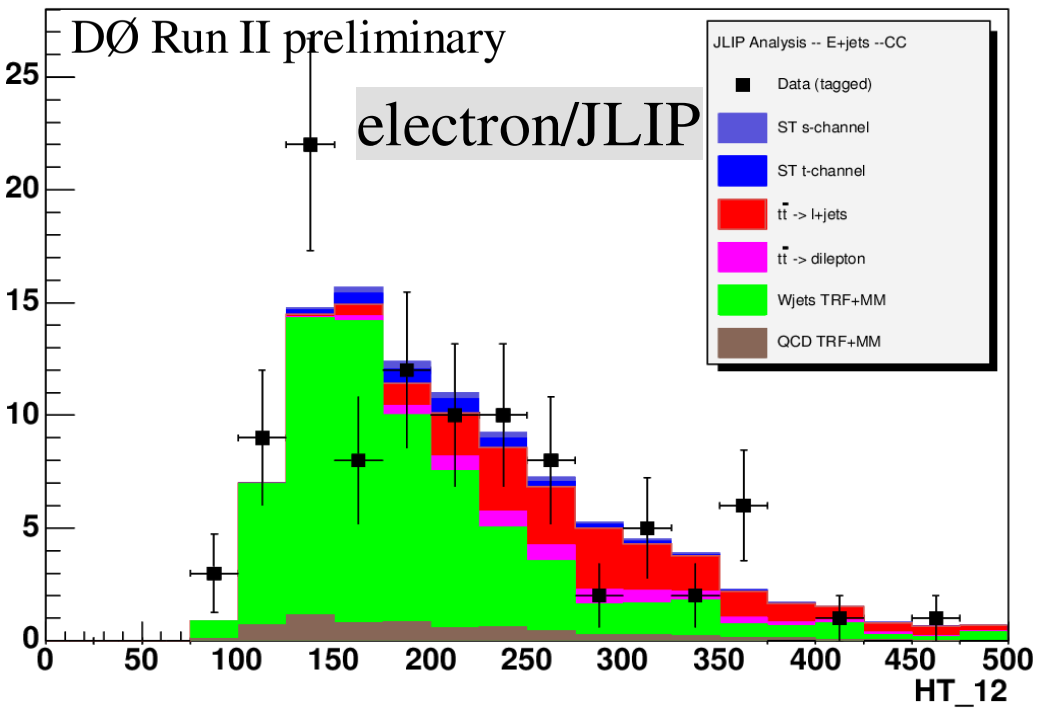
Event Yields: Number of Jets

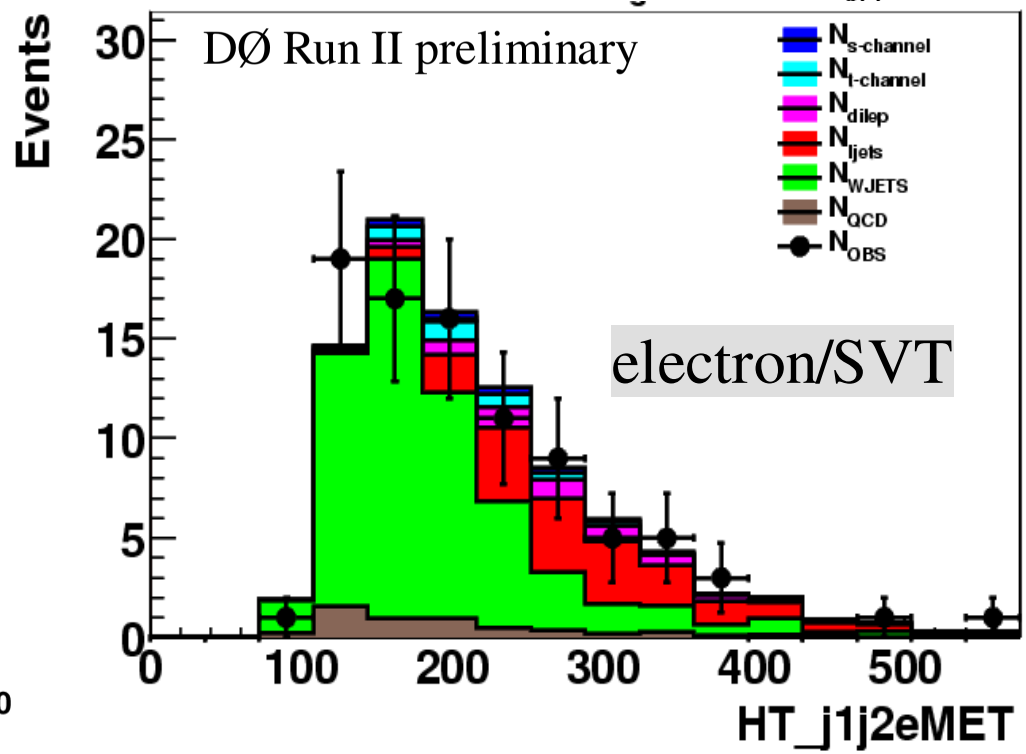


Event Yields: Event Energy HT

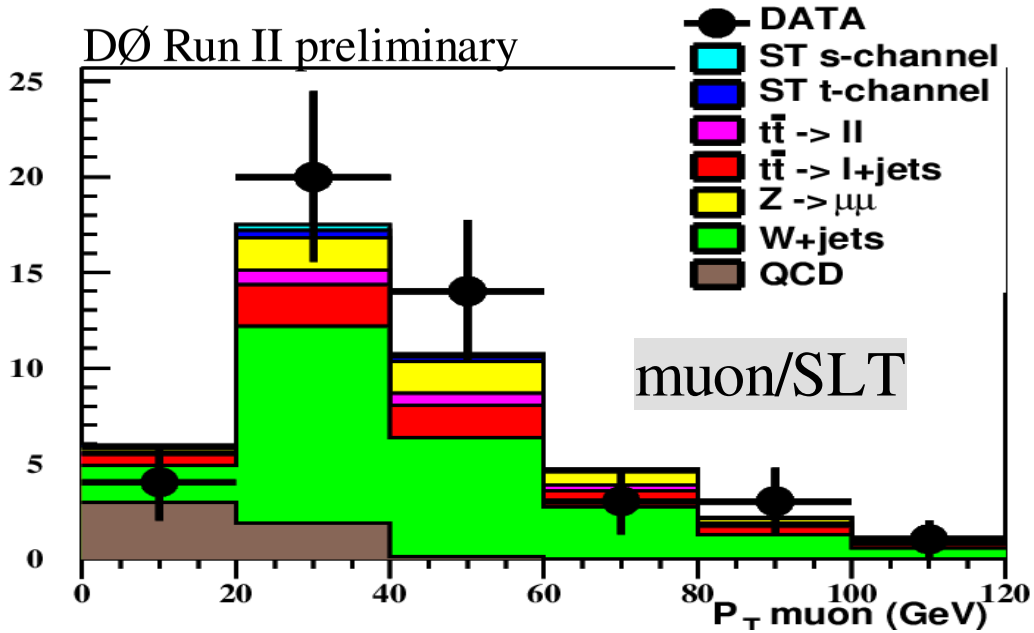


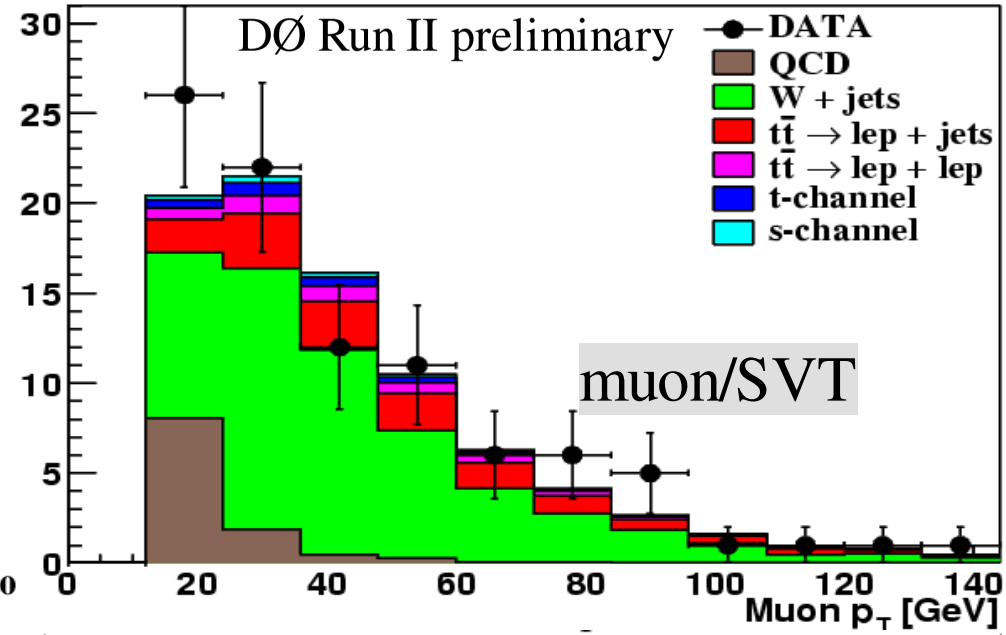


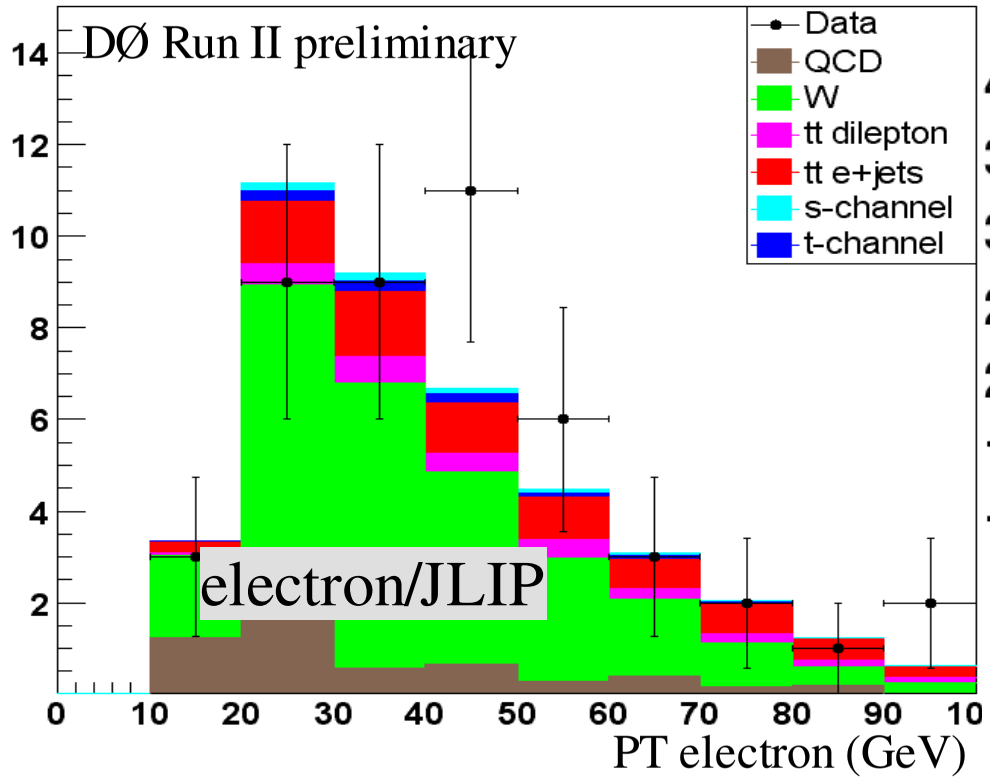


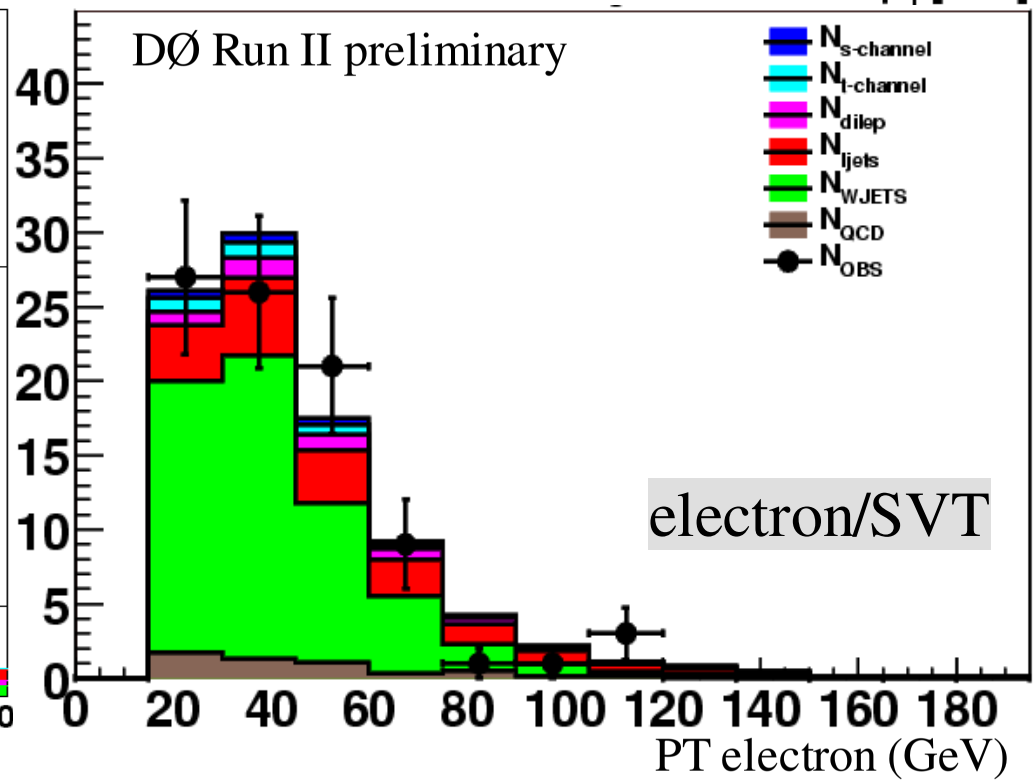


Event Yield: Lepton PT









Preselection Event Yield

- Individual channels and combinations
  - Combine electron, muon; SLT, SVT
  - Cannot combine with JLIP: lifetime taggers correlated
- Observed # of events:
  - Observed (SLT+SVT): 279
  - Predicted background (SLT+SVT): 255.9 ±18.5
  - Expected from single top (s+t channel): 11.7 ±1.2
  - Slight excess of events, consistent with background fluctuation
- Estimate sensitivity to signal at preselection level: expected cross section limits
  - Modified frequentist approach (CLs method)
    - Identical to Bayesian in this case, will also use Bayesian in the future
  - Include all systematic uncertainties and correlations
  - Separately for s-channel, t-channel, s+t combined

Expected Limits after Preselection

Channel	Electron	Muon	$e+\mu$	$e+\mu$ with SLT
s-channel				
SLT	22.8	26.1	18.2	—
SVT	13.5	18.0	12.1	11.5
JLIP	15.0	—	—	16.0
t-channel				
SLT	34.8	42.7	28.1	—
SVT	18.2	26.0	18.6	19.1
JLIP	20.8	—	—	17.4
s- and *t*-channel				
SLT	29.8	36.4	23.5	—
SVT	18.6	24.9	18.5	17.5
JLIP	18.3	—	—	16.0

Final Selection Cuts

to do!

- Apply simple Final Cuts
  - Cut on variables that have well understood behavior
  - Cut on variables that separate
    - Single-top from background sources
    - s-channel from t-channel
- Estimate Background composition after Final Cuts
- Derive cross section limit after Final Cuts

Summary

- Single Top Physics is an exciting new branch of Top Quark Studies
- The DØ detector is performing well
  - Data taking efficiency, trigger
  - Reconstruction of Physics objects
- We have started the Search for Single Top Production in Run II 6 months ago
  - Sensitivity already better than Run I limit
- We have built a solid foundation
  - To set limits on single top production
  - To work towards observation as we collect more data and make further improvements to the analysis

Outlook

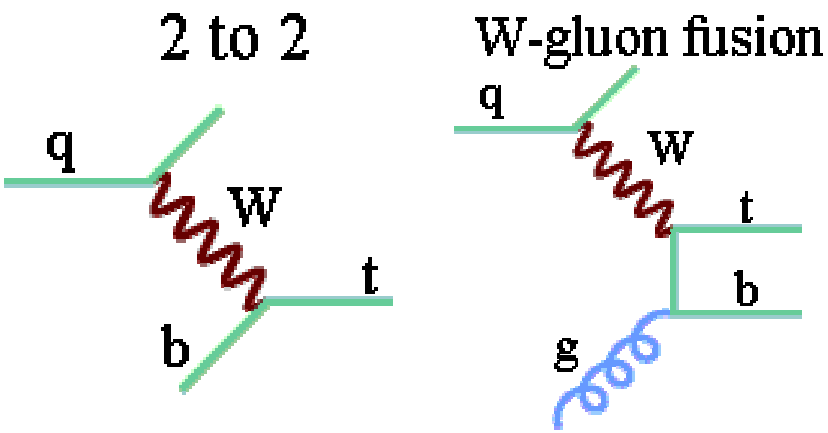
- We will set a limit on Single Top production in the near future
  - s-channel
  - t-channel
  - combined s and t-channel
- We are on our way to setting tight limits on Single Top production
  - and towards observation as we collect more data

Stay Tuned!

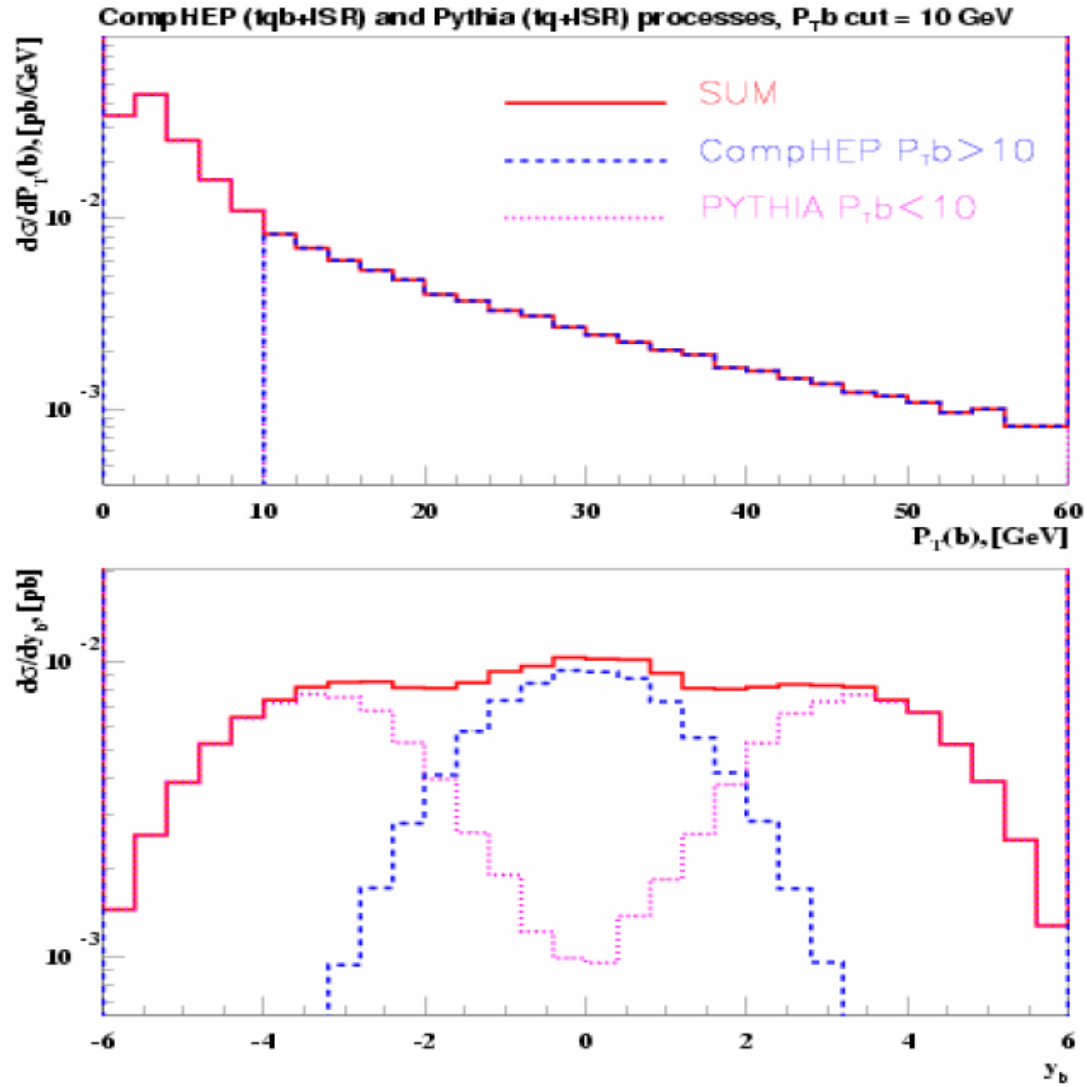
Supporting Slides

MC Modeling

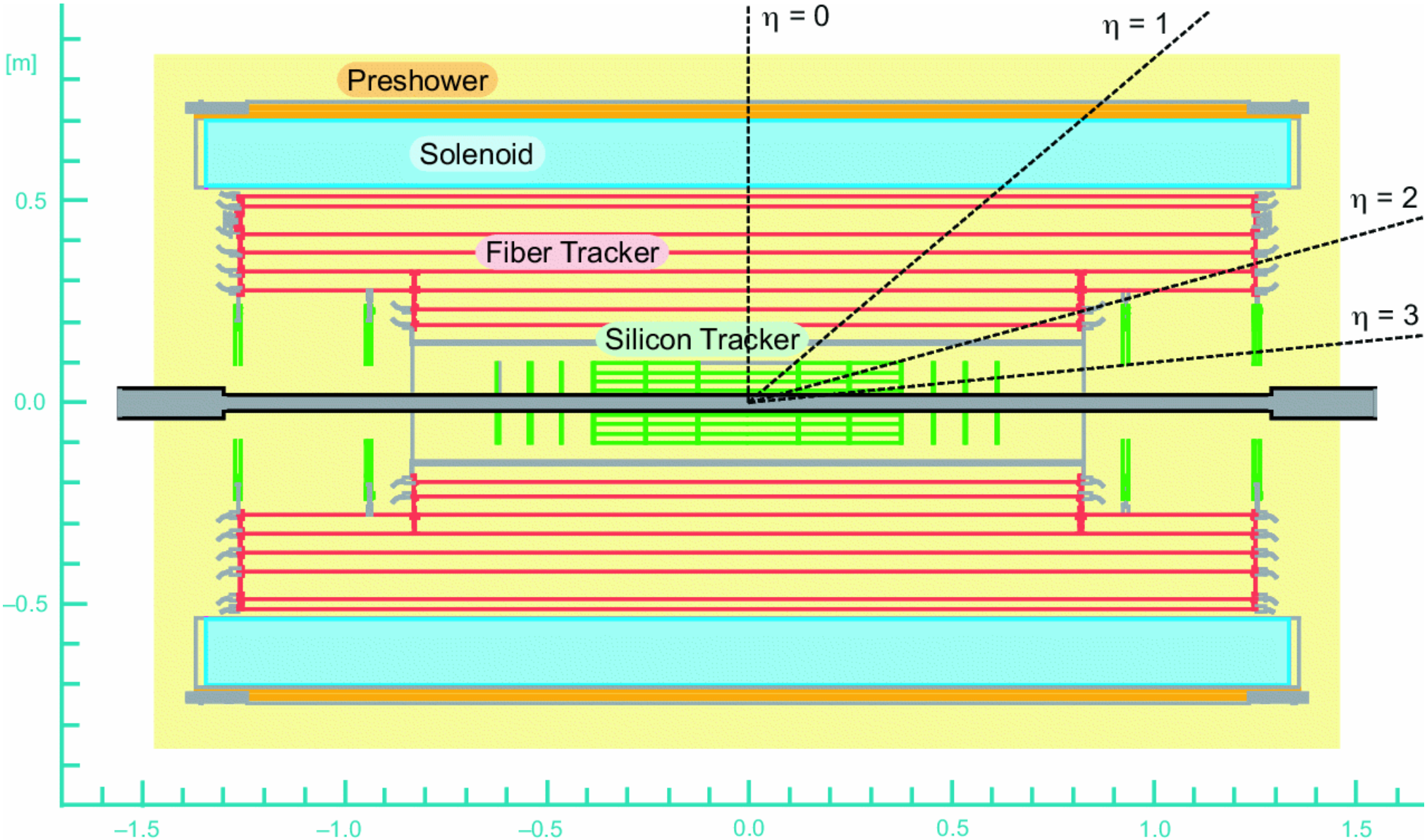
- Single Top modeling: CompHep
  - gives NLO-corrected distributions, not just LO diagrams
  - including full spin correlations
- t-channel problem:
  - how to match 2 to 2 with W-gluon fusion



solution:
phase-space matching
  - b from Pythia for soft region
  - ME generator for hard region

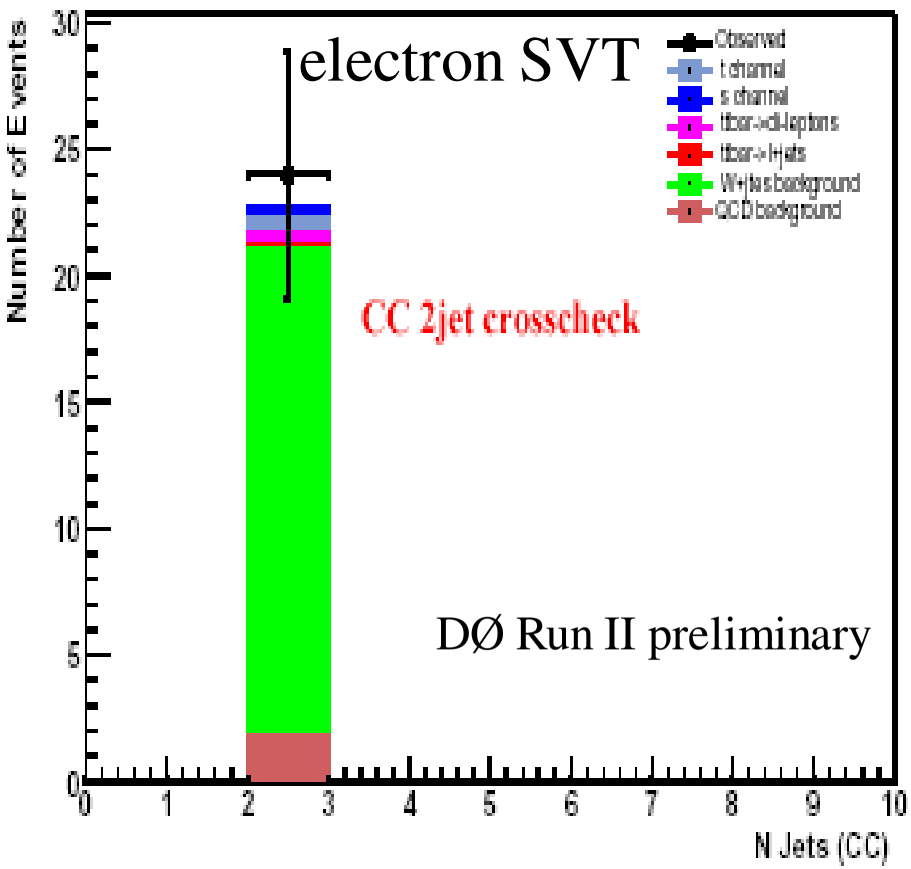


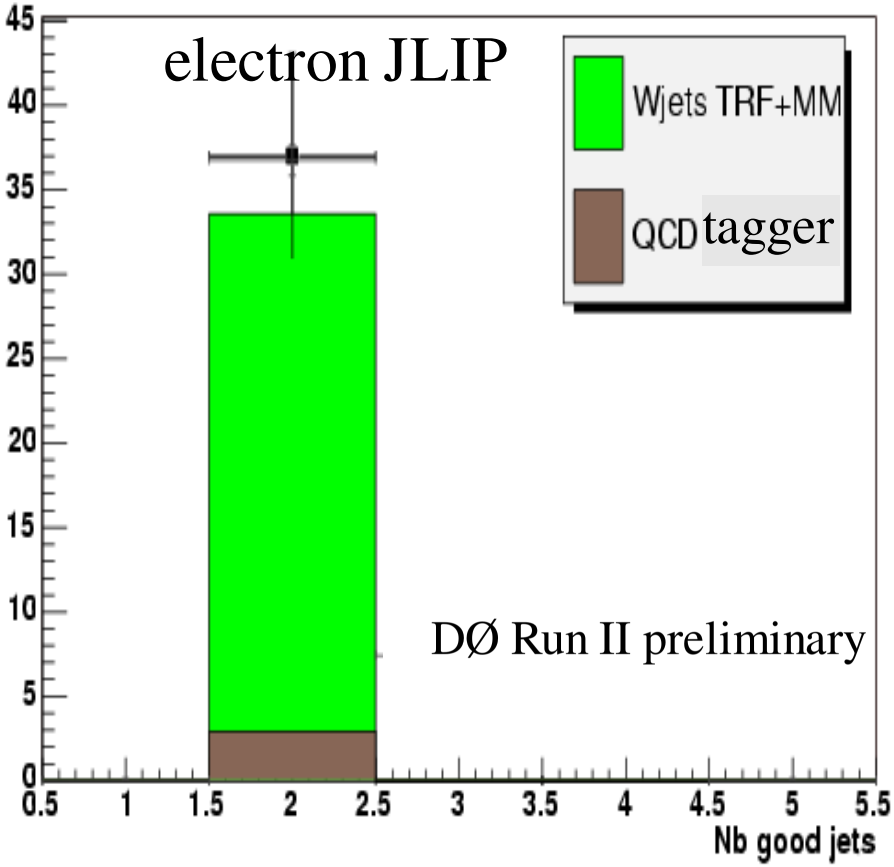
Run II DØ Tracking



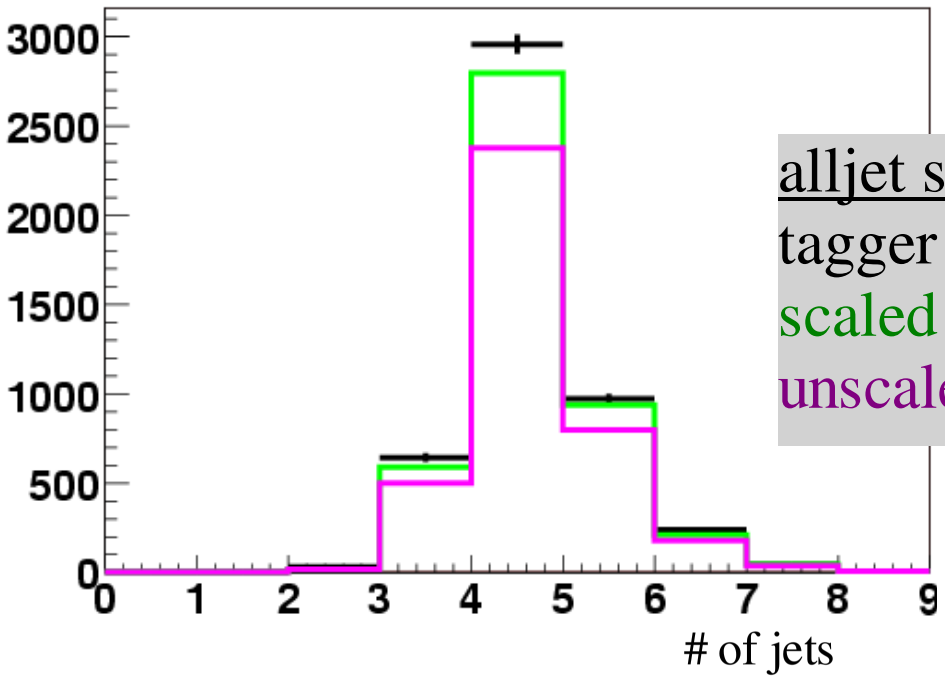
Inclusive TRF cross-checks

- Z+^{3}2jet sample:
  - SVT: TRF prediction: 15.7 events, tags found: 17
  - JLIP: TRF prediction: 14.9 events, tags found: 20
- W cross-check sample
  - muon channel SVT: prediction: 31.6, tags found: 27

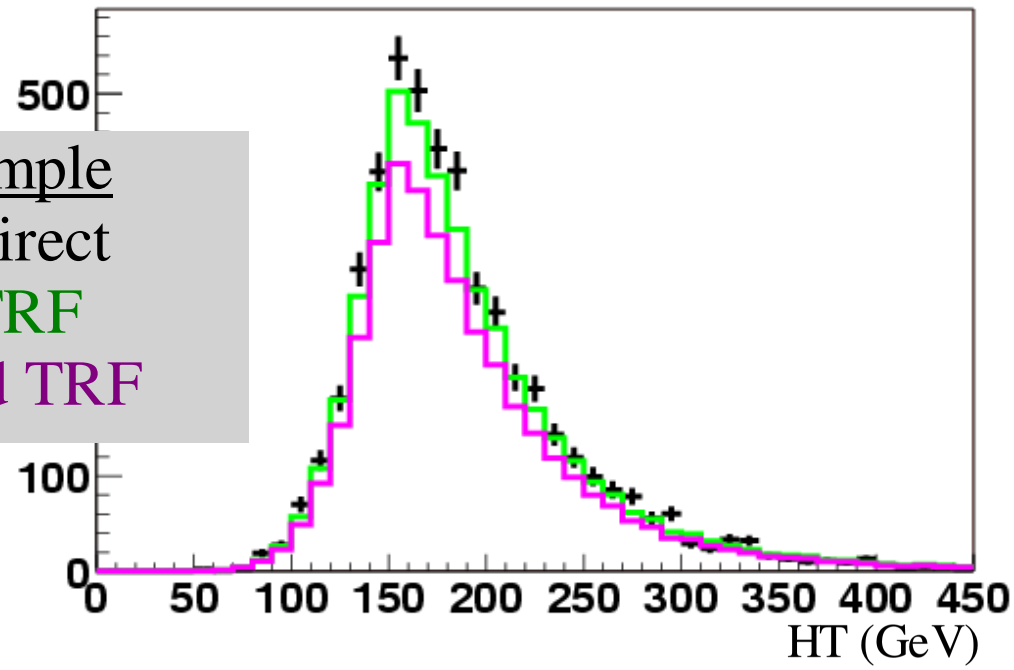


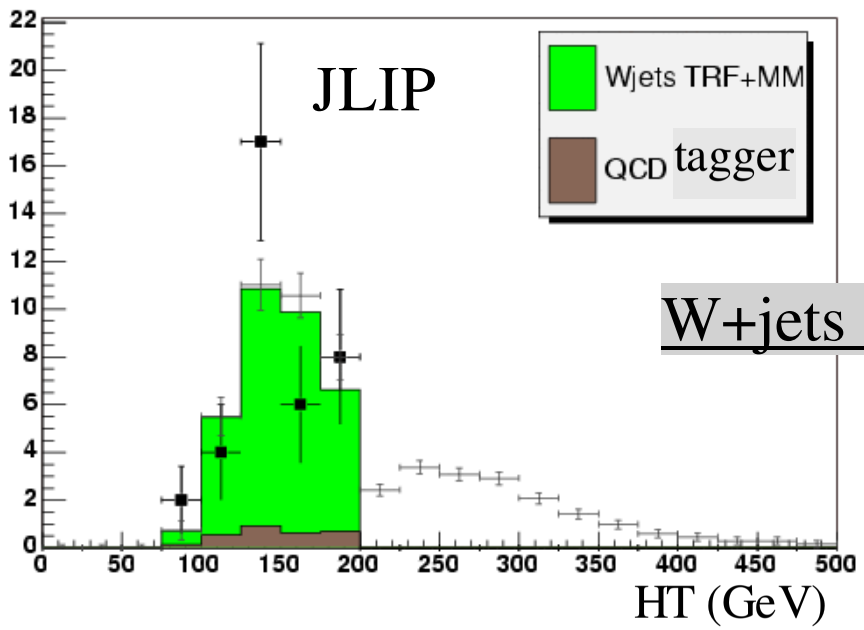


inclusive TRF cross-checks

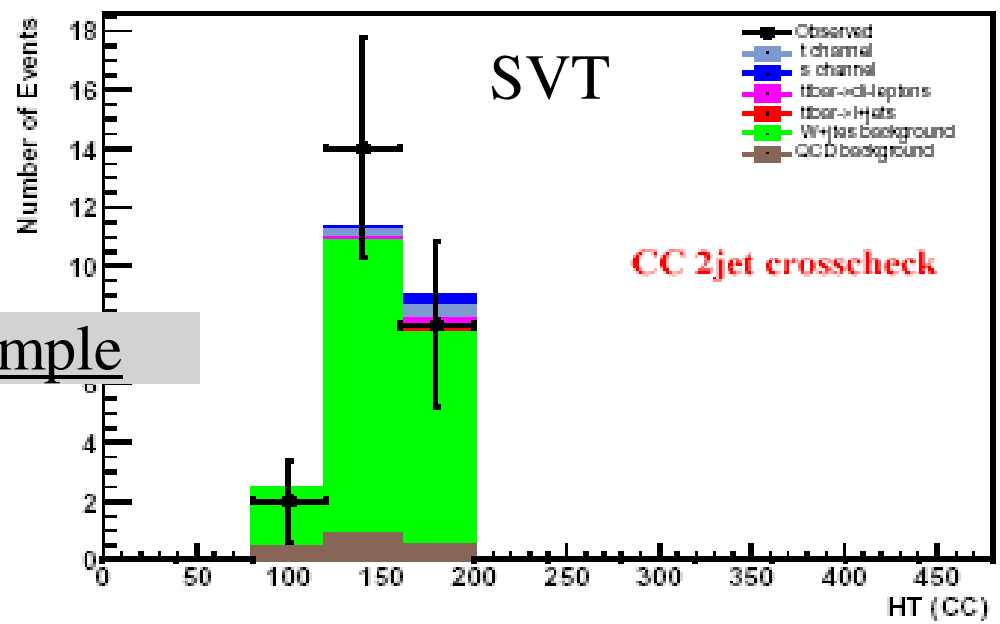


alljet sample
tagger direct
scaled TRF
unscaled TRF

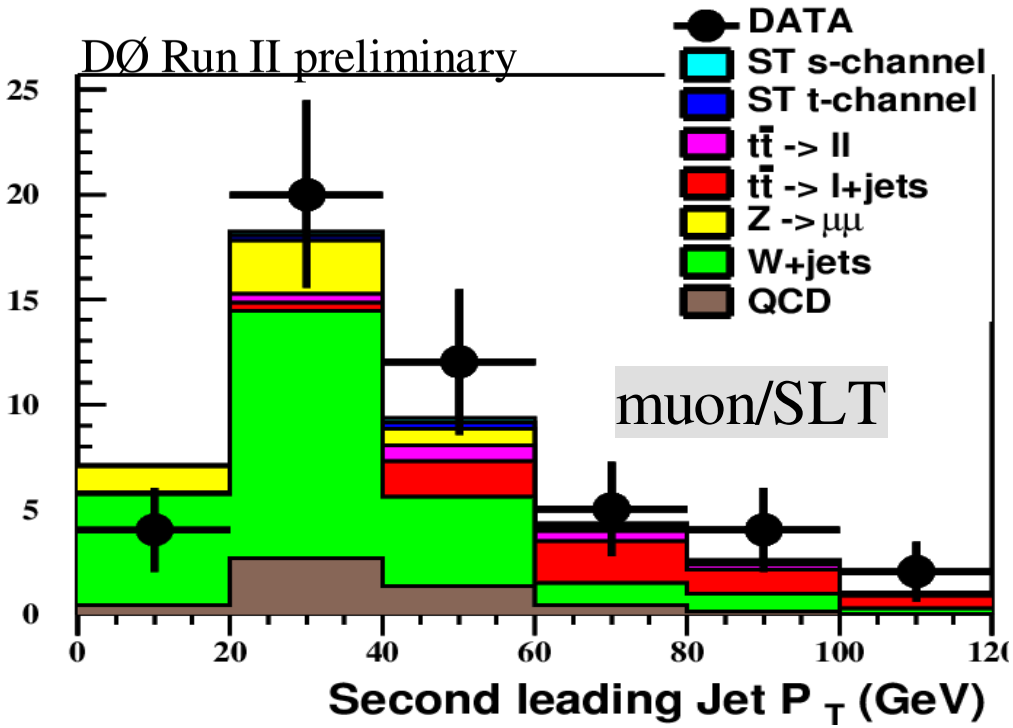


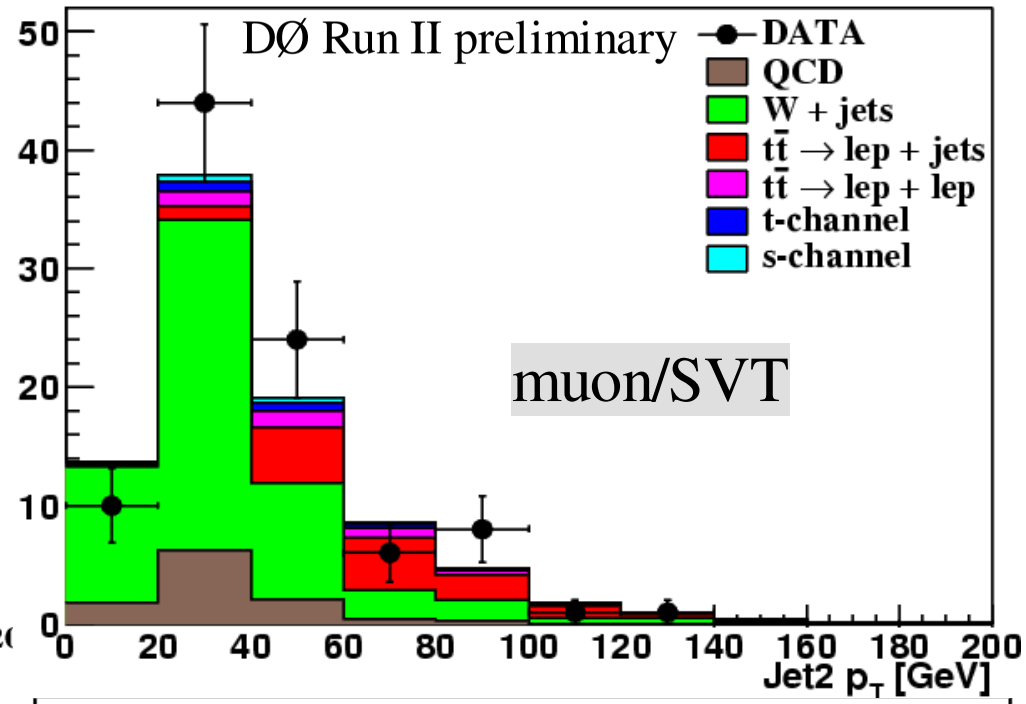


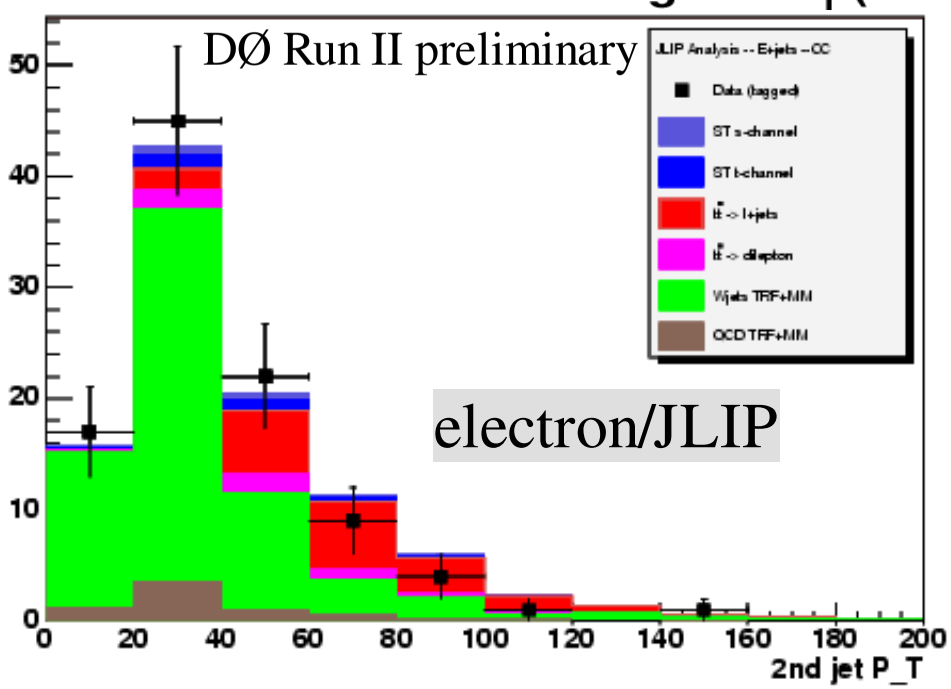
W+jets sample

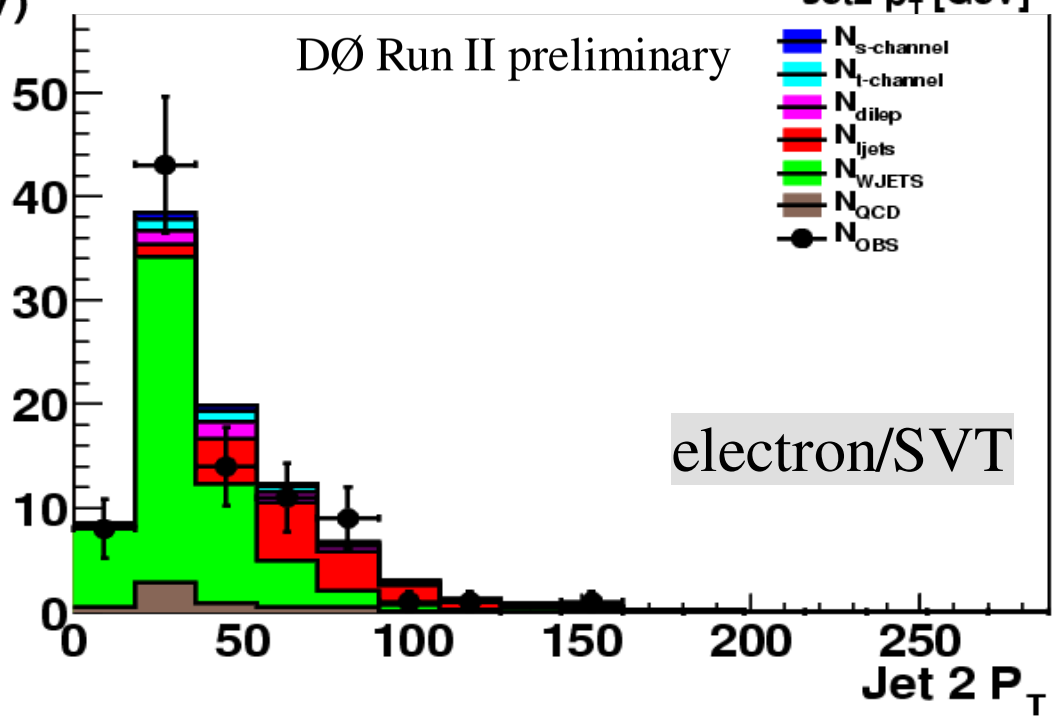


Event Yield: 2nd leading jet PT

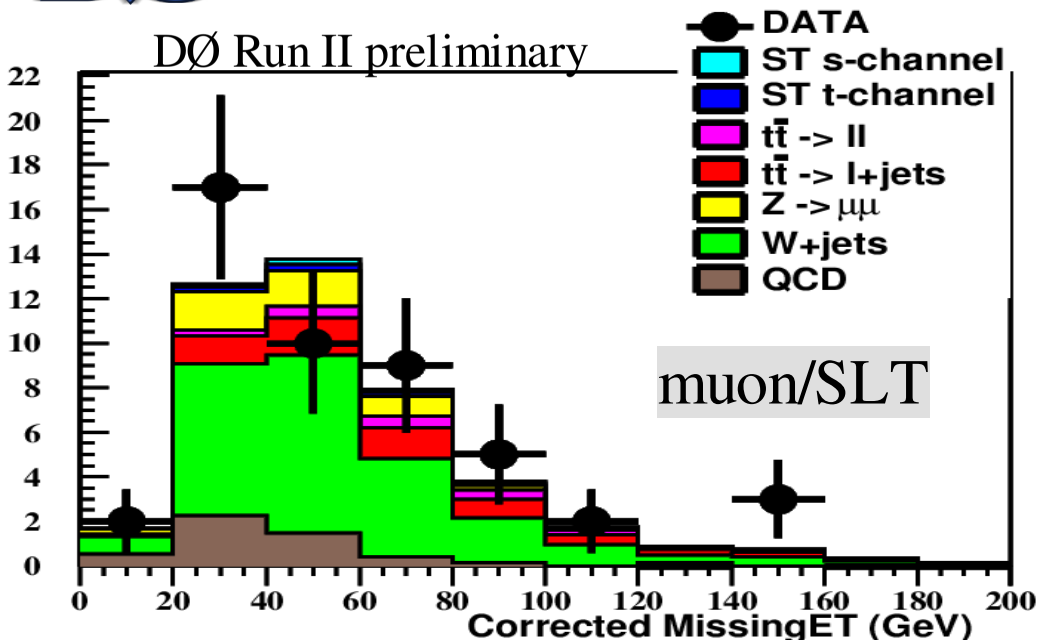


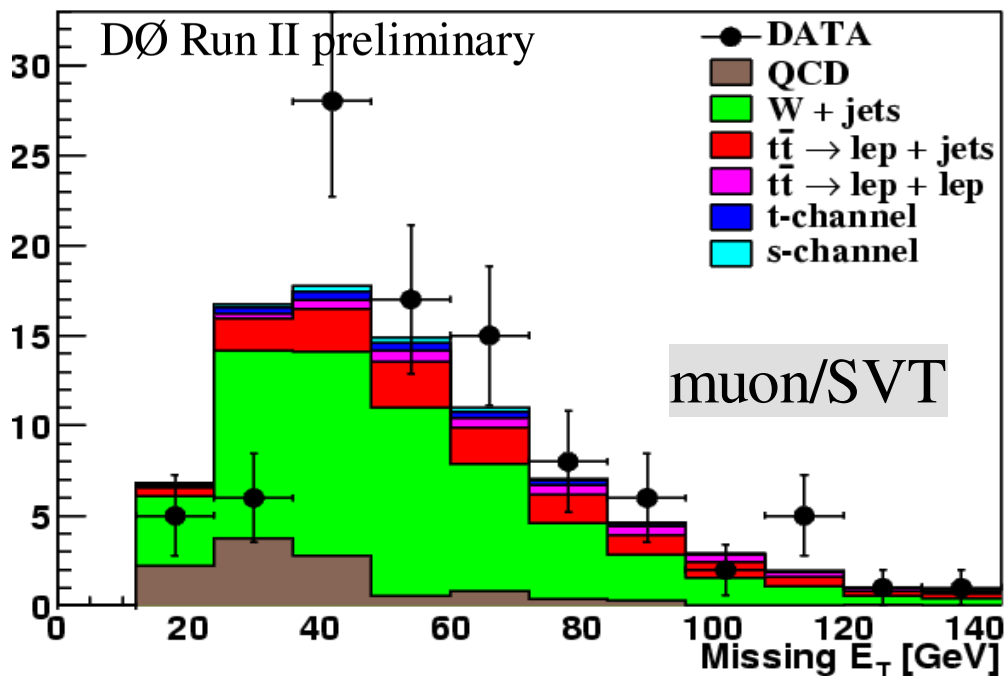


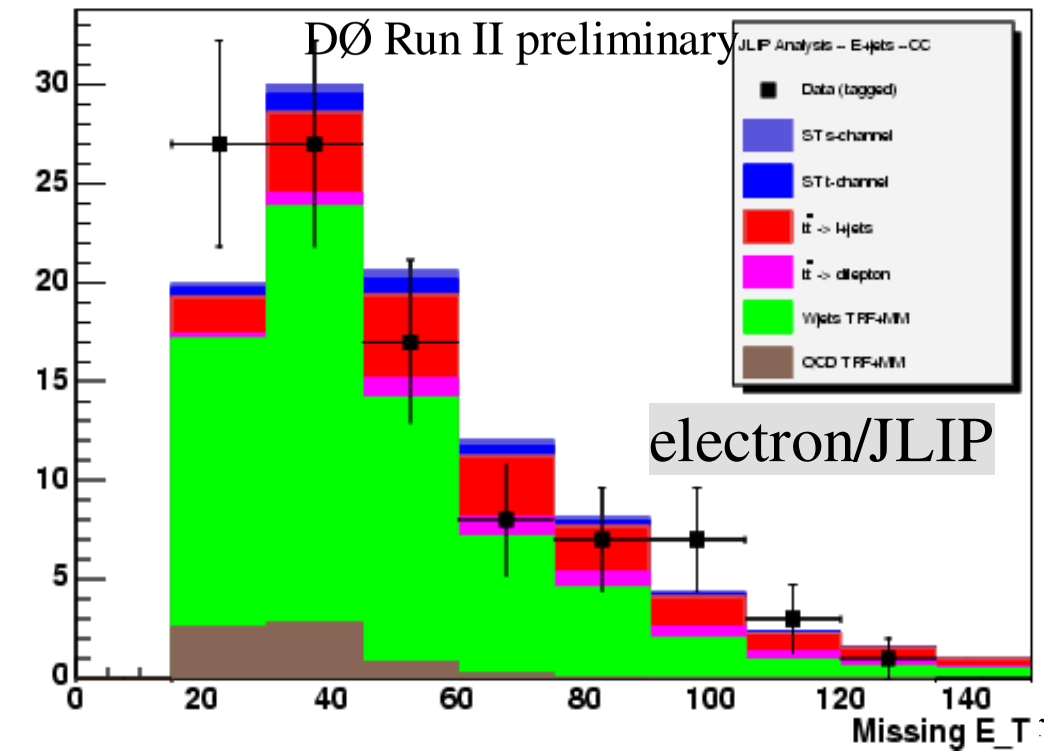


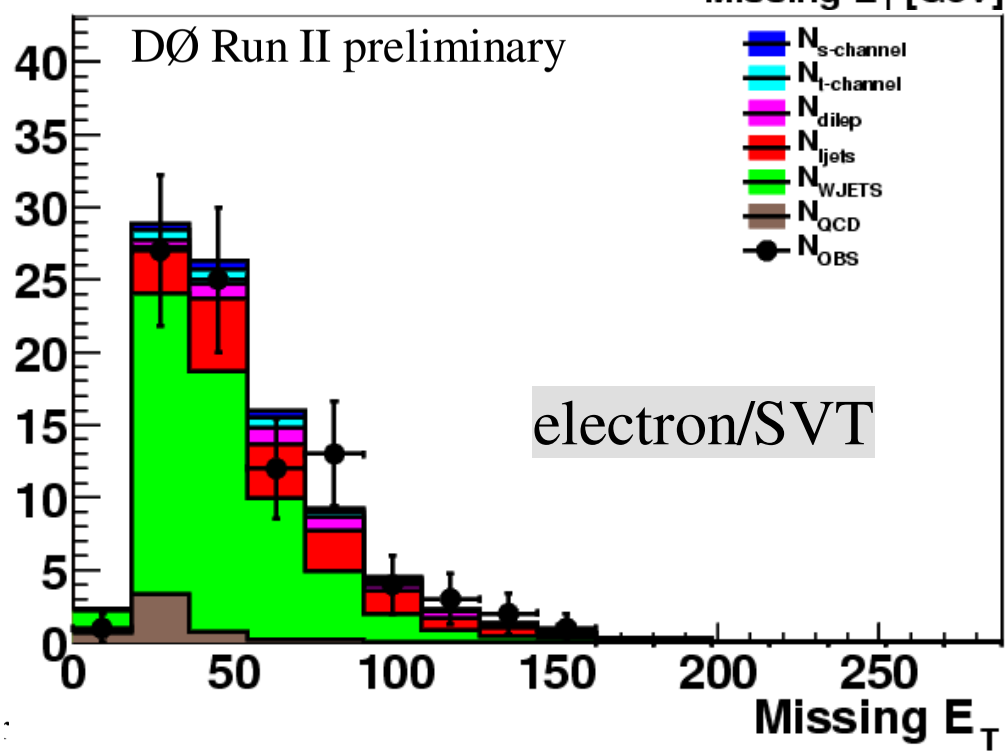


Event Yield: MET







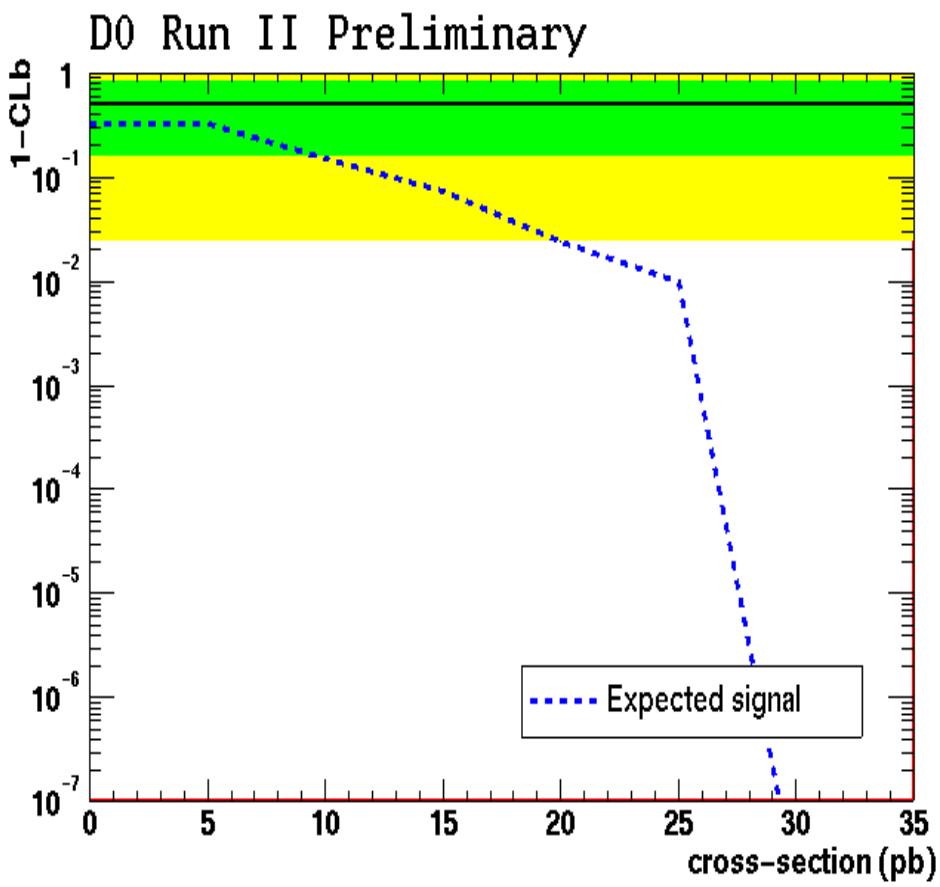


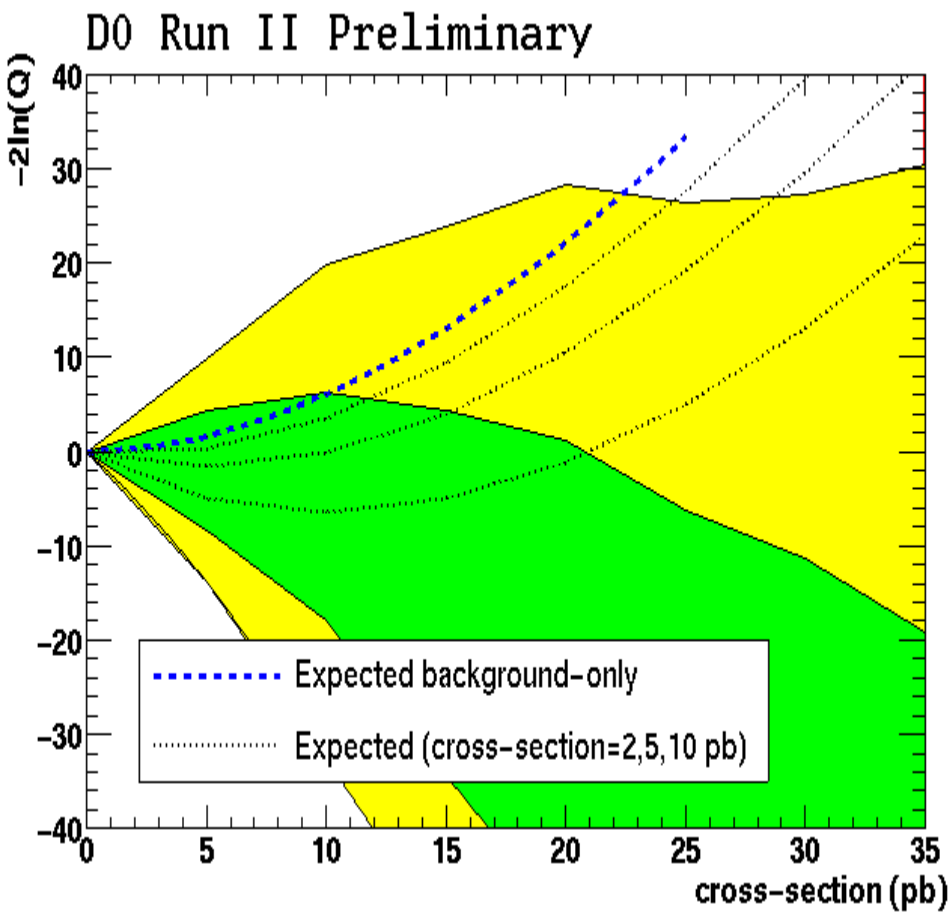
Event Yields

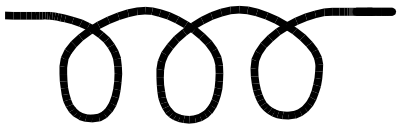
	Electron Channel (CC)			Muon Channel	
	SLT	SVT	JLIP	SLT	SVT
Signals					
MC tb	0.67 ± 0.14	1.87 ± 0.46	1.88 ± 0.46	0.63 ± 0.13	1.38 ± 0.35
MC tqb	0.95 ± 0.20	3.14 ± 0.76	3.20 ± 0.82	0.88 ± 0.19	2.19 ± 0.56
MC tb+tqb	1.62 ± 0.24	5.01 ± 0.89	5.08 ± 0.94	1.51 ± 0.23	3.57 ± 0.67
Backgrounds					
MC $t\bar{t} \to l$+jets	7.00 ± 1.56	18.38 ± 4.75	19.29 ± 5.31	6.25 ± 1.36	14.27 ± 3.59
MC $t\bar{t} \to ll$	2.60 ± 0.55	4.93 ± 1.22	5.29 ± 1.34	2.18 ± 0.47	4.30 ± 1.09
MC $Z \to \mu\mu$+jets	—	—	—	4.79 ± 0.86	—
W+jets + fake-l data	31.14 ± 5.15	63.54 ± 12.28	71.68 ± 13.73	29.5 ± 4.99	67.02 ± 11.81
Sum of bkgds	40.74 ± 5.41	86.85 ± 13.23	96.26 ± 14.78	42.72 ± 5.26	85.59 ± 12.39
Sum of bkgds for tb	41.69 ± 5.41	89.99 ± 13.25	99.46 ± 14.80	43.6 ± 5.27	87.78 ± 12.40
Sum of bkgds for tqb	41.41 ± 5.41	88.72 ± 13.24	98.14 ± 14.79	43.35 ± 5.27	86.97 ± 12.39
Signal data	49 ± 7	88 ± 9	99 ± 10	48 ± 7	94 ± 10

Modified Frequentist Method

- CLs: ratio of confidences: CL_{s+b}/CL_b
- Q: ratio of likelihoods L(x,s+b)/L(x,b)
- systematics:
  - include all systematic uncertainties and their correlations





Expected Limit
(statistical uncertainty only)

Channel	Electron	Muon	$e+\mu$	$e+\mu$ with SLT
s-channel				
SLT	19.3	20.0	13.2	
SVT	9.6	12.9	7.4	6.4
JLIP	9.8	—	—	7.7
t-channel				
SLT	29.4	32.5	20.9	
SVT	12.9	18.2	10.0	8.9
JLIP	13.0	—	—	10.8
s- and *t*-channel				
SLT	25.6	28.1	17.5	
SVT	11.5	15.6	8.9	7.8
JLIP	11.7	—	—	9.5